Improving Concrete Sustainability by Designing and Specifying for Durability

R. Doug Hooton,
NSERC/CAC Industrial Research Chair in Concrete Durability & Sustainability

UNIVERSITY OF TORONTO
DEPT. CIVIL ENGINEERING

& John A. Bickley, Consultant, Retired

Minnesota Concrete Council Nov. 14, 2013

Wine Fermentation in Concrete Tanks

"Concrete wine vessels are not inert, and harbour an ecosystem of yeast and bacteria that affects the wine. They can live from vintage to vintage in the rough surface of the concrete, and those bacteria and yeast help the fermentation."

http://www.cbc.ca/news/technology/canadian-winemaker-says-concrete-tanks-worth-their-weight-1.2355972

Durable Concrete Performs Better than the Leafs (Rewarding poor performance for 45 years)

But maybe this is the year the bags come off !

NSERC/CAC Chair Research in Concrete Durability & Sustainability

1) Durability research including:
   i. Sulfate resistance at low-temperatures;
   ii. de-icer scaling resistance: developing better tests
   iii. chloride resistance & fluid transport properties;
   iv. effects of cement alkali on SCM mitigation of ASR
   v. Improving reliability of rapid ASR tests
2) Develop new durability-based performance tests and implement them in CSA and ASTM standards and specifications.
3) Develop & promote use of performance –based specifications.

NSERC/CAC Chair Research in Concrete Durability & Sustainability

4) Reduce CO_2 footprint of concrete mixtures:

i. Research on Portland-limestone cements & field trials.

ii. Research on synergy of PLC-SCM binder concretes.

iii. Research and standardization of combined total aggregate gradation/particle packing to reduce paste content and improve durability.

iv. Evaluating non-portland cement binders & microfillers

v. Durability of concrete incorporating recycled concrete aggregates.

Manufacture of Portland Cement

- Contributes to 5% of global CO_2 emissions*
- Contributes to 3.8% of global energy use*
- For every tonne of cement produced:
  - 0.8 – 1.0 t of CO_2 produced (depending on kiln operation)
  - 1,700 kWh of energy consumed/t
  - 1.5 t of raw material required
  - 3,300,000 t cement produced globally in 2010

* Source: World Resources Institute

Portland cement is the primary binder in Concrete

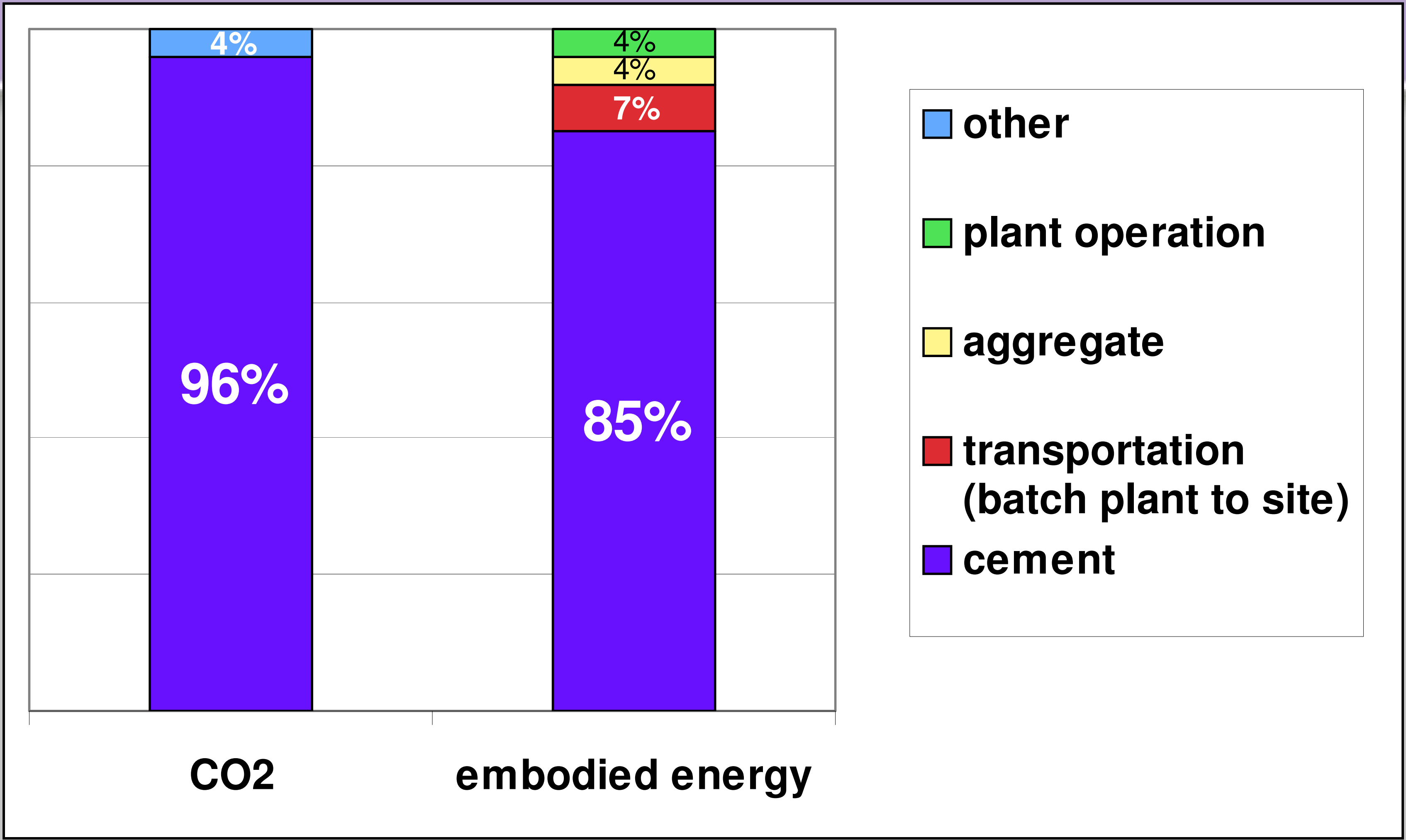
- Portland Cement is manufactured from limestone and shale rocks that have been fired at 1450 C to form a synthetic rock called clinker. This clinker is then crushed to a powder.
- When limestone is heated, it gives off CO_2.
  - $CaCO_3 \rightarrow CaO + CO_2 \uparrow$

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

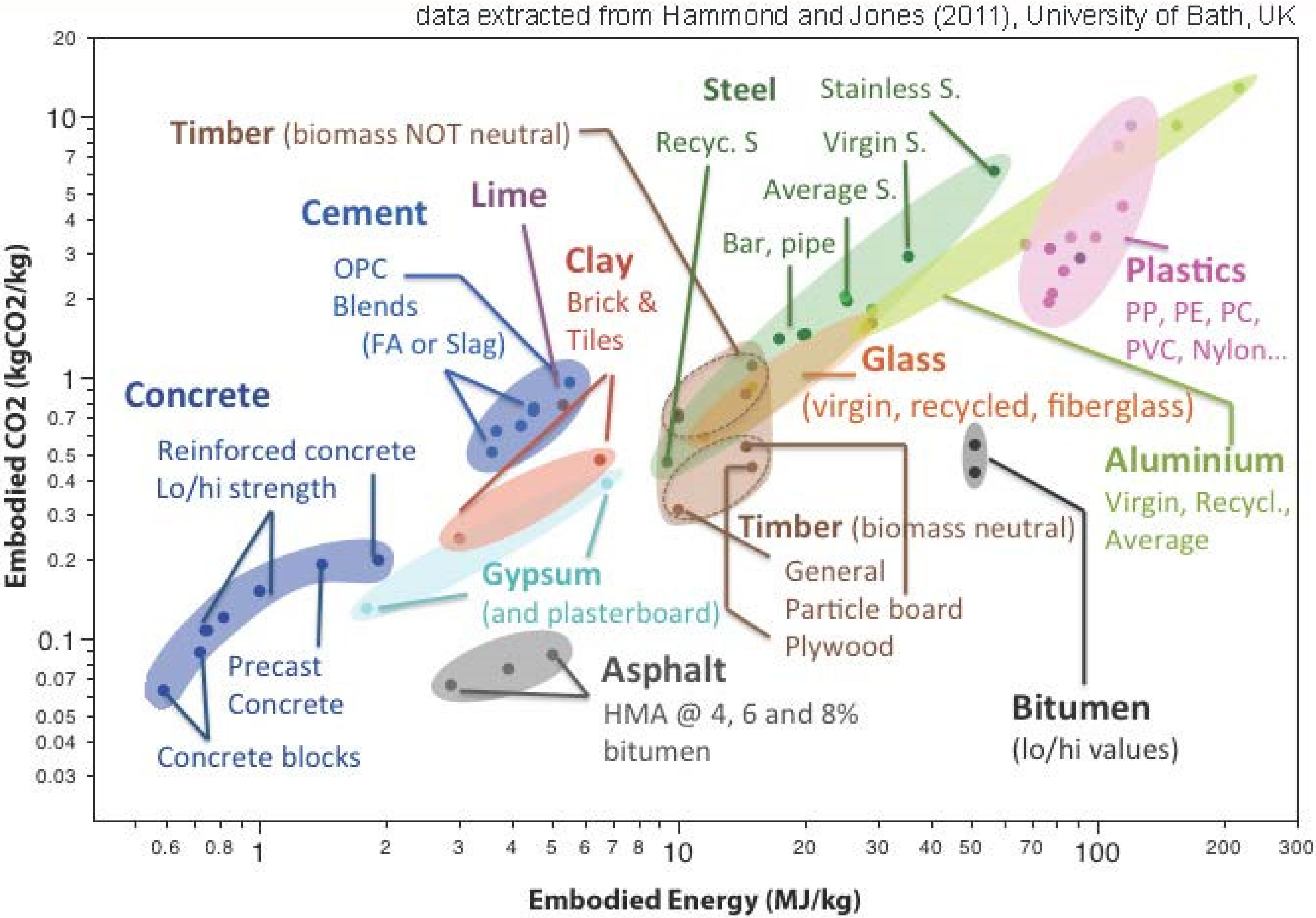
But Portland Cement is only one component of concrete

- Approximately 90% of the carbon footprint of concrete is from portland cement (assuming portland cement is used as the sole binder)
- So reducing the portland cement clinker component will have a major impact.

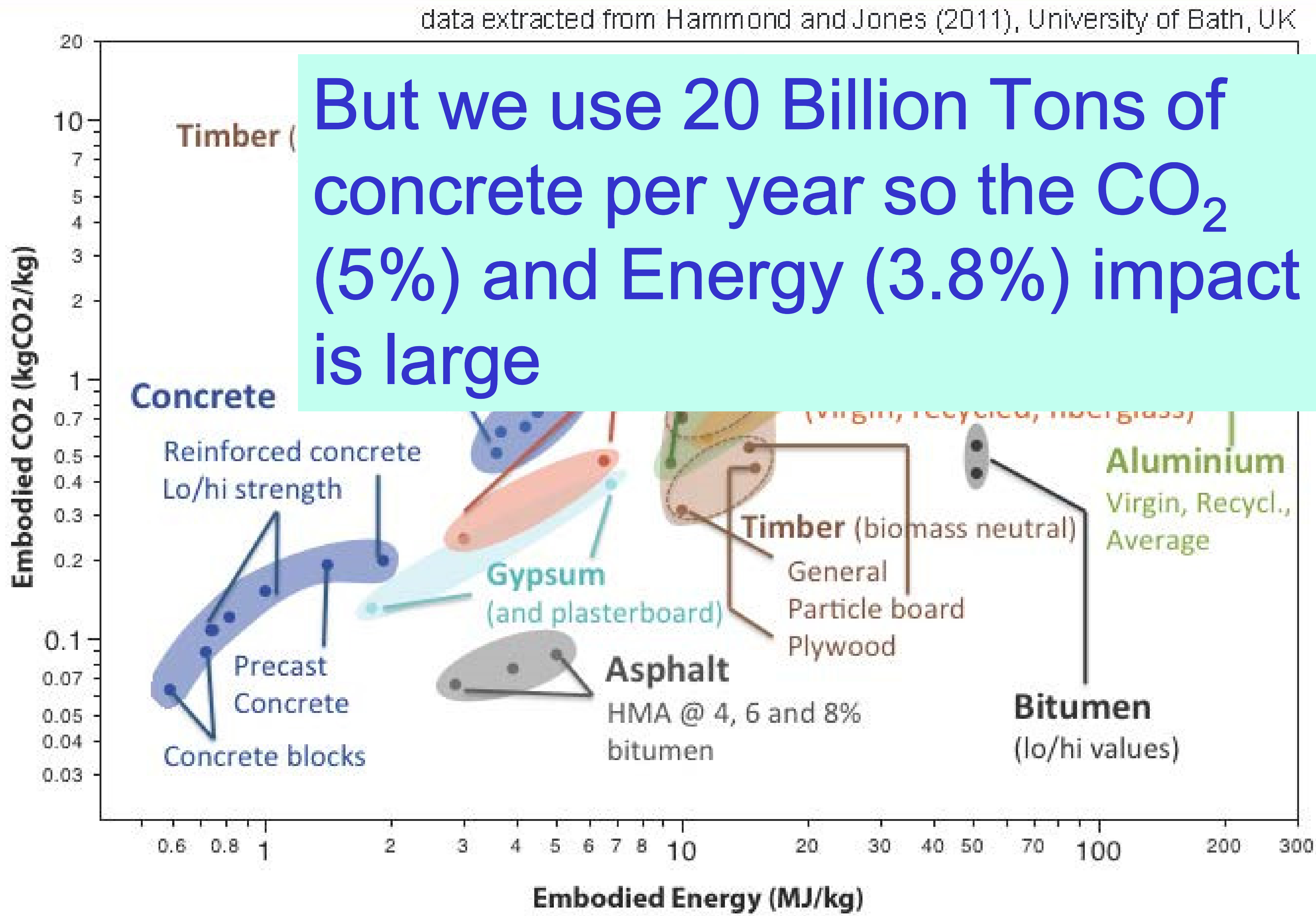
Plain Portland Cement Concrete



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



data extracted from Hammond and Jones (2011), University of Bath, UK
Embodied CO2 (kgCO2/kg)
Embodied Energy (MJ/kg)
20
10
7
5
4
3
2
1
0.7
0.5
0.4
0.3
0.2
0.1
0.07
0.05
0.04
0.03
0.6
0.8
1
2
3
4
5
6
7
8
10
20
30
40
50
70
100
200
300
Steel
Stainless S.
Recyc. S
Virgin S.
Average S.
Bar, pipe
Timber (biomass NOT neutral)
Lime
Cement
OPC
Blends
(FA or Slag)
Clay
Brick &
Tiles
Concrete
Reinforced concrete
Lo/hi strength
Precast
Concrete
Concrete blocks
Gypsum
(and plasterboard)
Asphalt
HMA @ 4, 6 and 8%
bitumen
Glass
(virgin, recycled, fiberglass)
Plastics
PP, PE, PC,
PVC, Nylon...
Aluminium
Virgin, Recycl.,
Average
Timber (biomass neutral)
General
Particle board
Plywood
Bitumen
(lo/hi values)



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

Construction vs Use

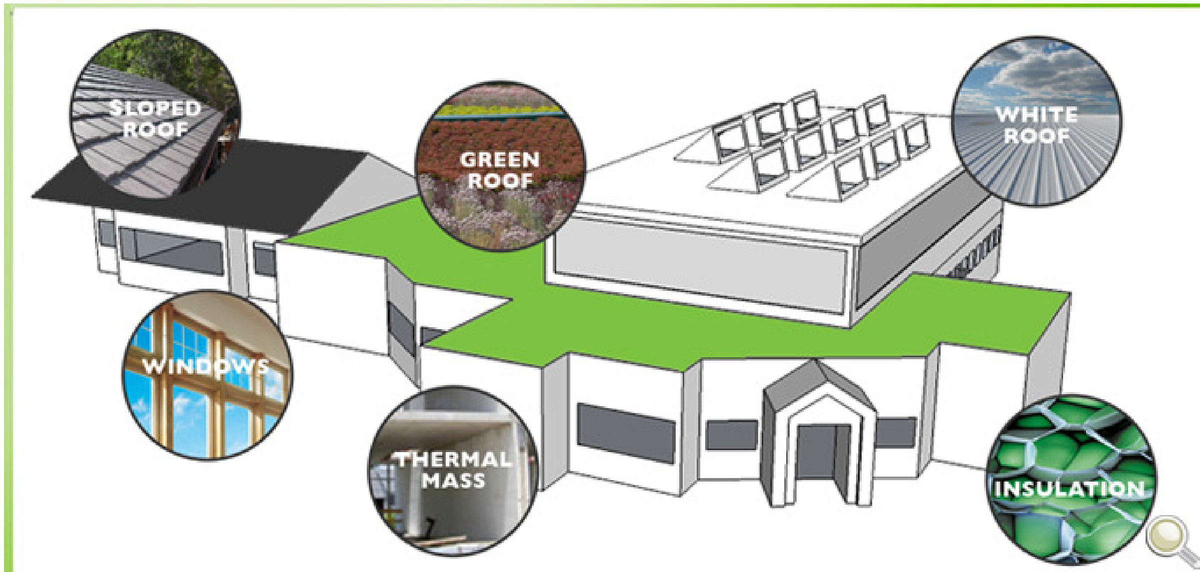
- In buildings, construction only accounts for ~10% of its lifetime energy and CO2
- ~90% is used for power, heating & air conditioning.
  - Using exposed concrete finishes reduces VOCs and its light color can reduce lighting needs.
  - Utilizing concrete's thermal mass and using concrete elements for pre-conditioning air will reduce HVAC needs.

RBC tower at Simcoe & Wellington St., Toronto

Earth Rangers Centre

near Toronto

- Concrete earth tubes pre-heat/cool incoming air into perimeter basement envelope
- Concrete floors, walls, roofs for thermal mass and with radiant heating/cooling pipes from ground source.
- Uses 90% less energy than typical building of its size



The bigger picture
(NRMCA Fact Sheet 2009)

- Concrete is resource efficient and the ingredients require little processing.
- Most materials for concrete are acquired and manufactured locally which minimizes transportation energy.
- Concrete building systems combine insulation with high thermal mass and low air infiltration to make homes and buildings more energy efficient.
- Concrete has a long service life for buildings and transportation infrastructure, thereby increasing the service life.
- Concrete pavement or exterior cladding, helps minimize the urban heat island effect --reducing the energy required to heat and cool homes and buildings.
- Concrete incorporates recycled industrial by-products such as fly ash, slag and silica fume that reduce embodied energy, carbon footprint and quantity of landfilled materials.
- Concrete absorbs CO_2 throughout its lifetime through carbonation, helping reduce its carbon footprint.

We can improve many concrete mix designs to reduce CO_2 footprints

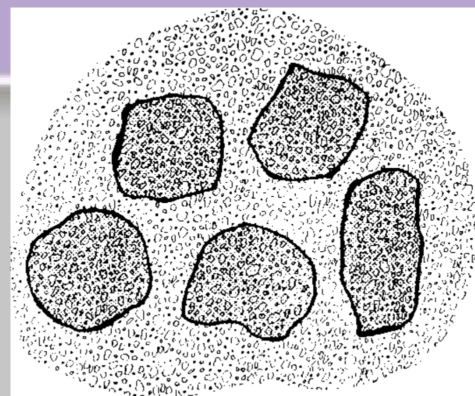
1. Optimization of combined aggregate gradations.---reduces cement content
2. Use of water reducing admixtures---reduces required cement content for a given w/cm
3. Use of portland-limestone cements (PLC)---reduces clinker content of cement
4. Use of SCMs---reduces portland cement content
5. Use of recycled aggregates, where appropriate

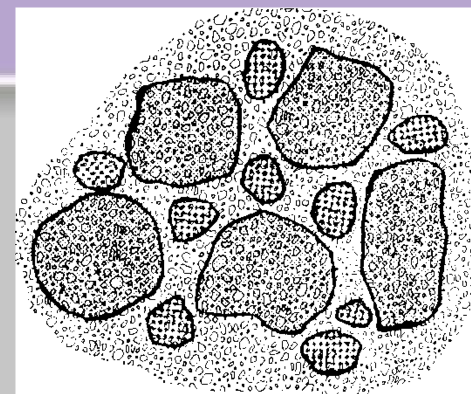
- And all, or most, can be done simultaneously!

1. Improving Aggregate Gradations

- Having to meet current specifications for meeting individual fine and coarse aggregate gradations can result in poorer particle packing and large portions of quarried and crushed stone being wasted.
- Microfine mineral fillers can also extend total aggregate gradations
- Current PhD of M. Anson-Cartwright

Optimizing Combined Aggregate Gradation and using Microfine Fillers





Typical Mix
Gap-graded

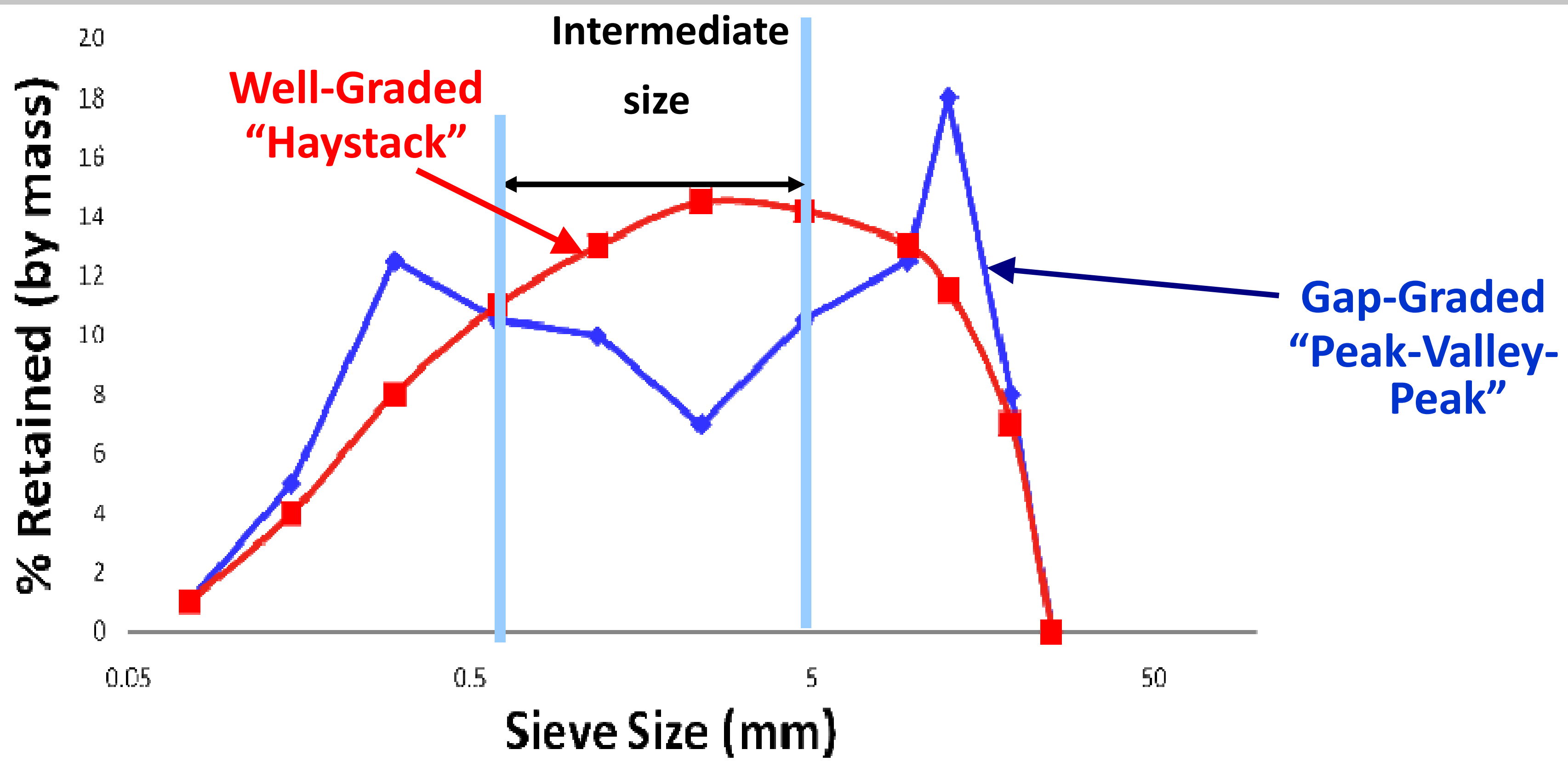
- Gap-graded; lack of intermediate particles
- No microfine fillers; lack of <75µm particles
- ↑ void content
- ↑ paste fraction required

Optimized Mix
Well-graded

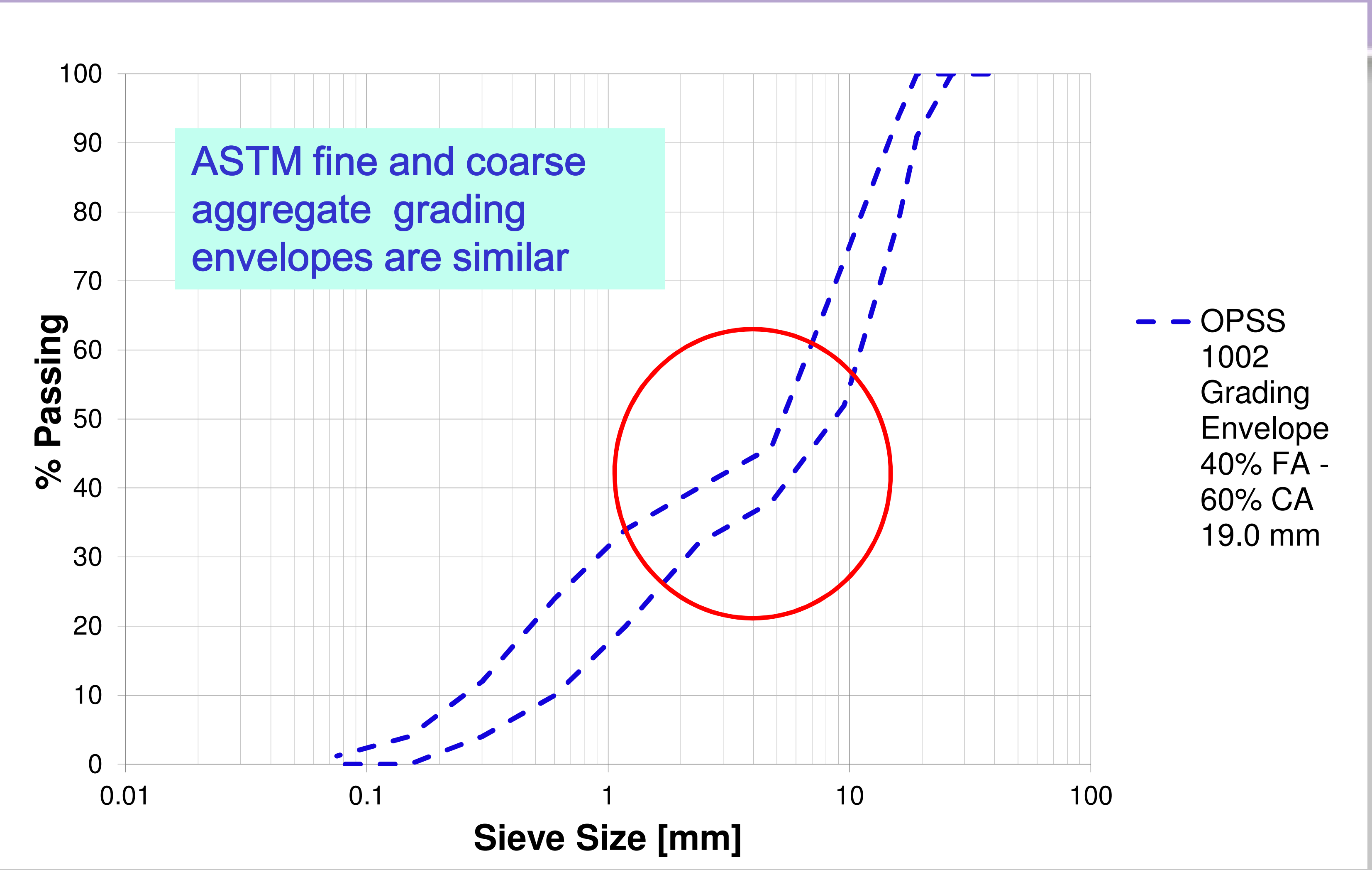
- **Well-graded; plenty of intermediate particles**
- **Microfine fillers; plenty of <75µm particles**
- **↓ void content**
- **↓ paste fraction required**

Optimizing the Total Aggregate Gradation

- A well-graded combined aggregate blend can be achieved by using optimization techniques, using low value or wasted aggregate fractions



The gap resulting from having to meet separate fine & coarse grading envelopes



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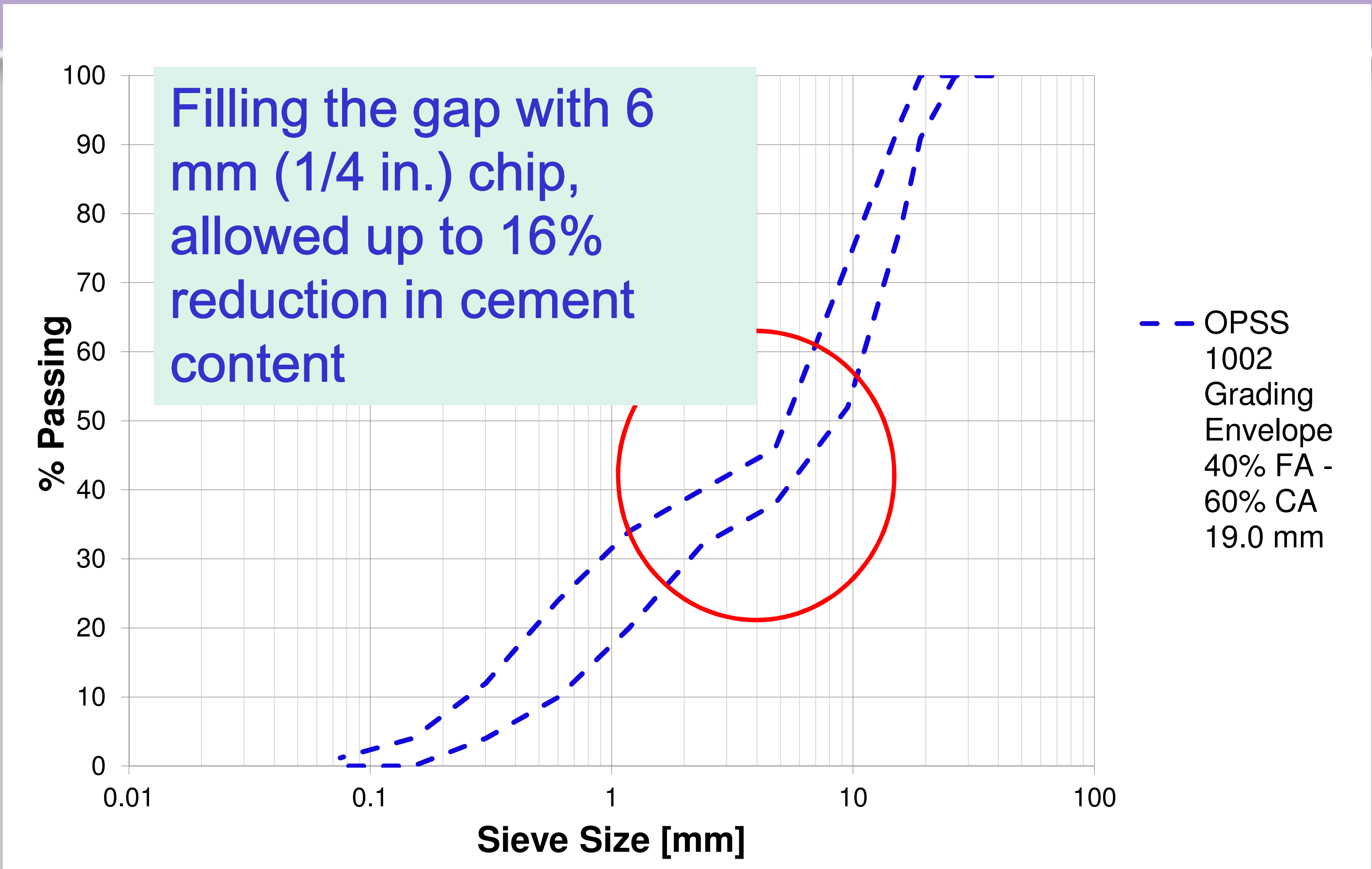


By optimizing the total aggregate gradation, binder contents in concrete can be reduced

By adding an intermediate size Coarse Aggregate (6.7mm (1/4 in.) chip from crushing operation):

- 16% reductions in 50 MPa bridge deck mixes were obtained (465 down to 390 kg/m^3) while meeting 1000 coulomb limit @ 56 days.
- 8% reductions in 35 MPa mixes were obtained (360 down to 330 kg/m^3) while still meeting 1500 coulomb limit @ 56 days.
- Partly due to this work, CSA A23.1 is adopting an option for use of combined total aggregate gradations.

MASc of Majella Anson-Cartwright 2011

4. Portland-Limestone Cement

- In 2008-09, CSA A3000/A23.1 introduced portland-limestone cements with up to 15% interground limestone.
- These were adopted in the Canadian and Provincial Building Codes in 2011)
- Its use has a direct effect on reducing point-source CO_2 emissions at cement plants by ~10% compared to portland cements.
- Similar cements have also been used in US using ASTM C1157 for about 10 years.
- In 2012, ASTM C595 adopted 15% limestone as a new category (Type IL and some Type IT ternary cements). The ACI 318 building code allows use of C595 cements.

How Do Portland-Limestone Cements Perform in the Field?

- Equal or improved to portland cements
  - Strength
  - Set time
  - Water demand
  - Compatibility with fly ash/slag
  - Compatibility with admixtures
- Improved finishability
- Lower environmental impact

PLC Trial 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 +25% SLAG	PLC + 25% SLAG
Shrinkage (28d drying)	**0.038%**	**0.038%**
Strength (MPa)		
1	**9.5 (1380 psi)**	**10.3 (1490 psi)**
3	**19.3**	**19.4**
7	**25.6**	**26.8**
28	**36.9 (5350 psi)**	**37.9 (5500 psi)**
56	**38.9**	**38.0**
91	**40.7 (5900 psi)**	**40.2 (5830 psi)**
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**

b) PLC Paving on Highway 401 Sept 27, 2010

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

2010 PLC Paving Trial

- New Highway 401 Eastbound exit to Highway #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 (1.5 in.) Aggregate
- Pavement was 4.25 m (13 ft)wide x 280 mm (11 in.) thick with pre-placed dowel baskets

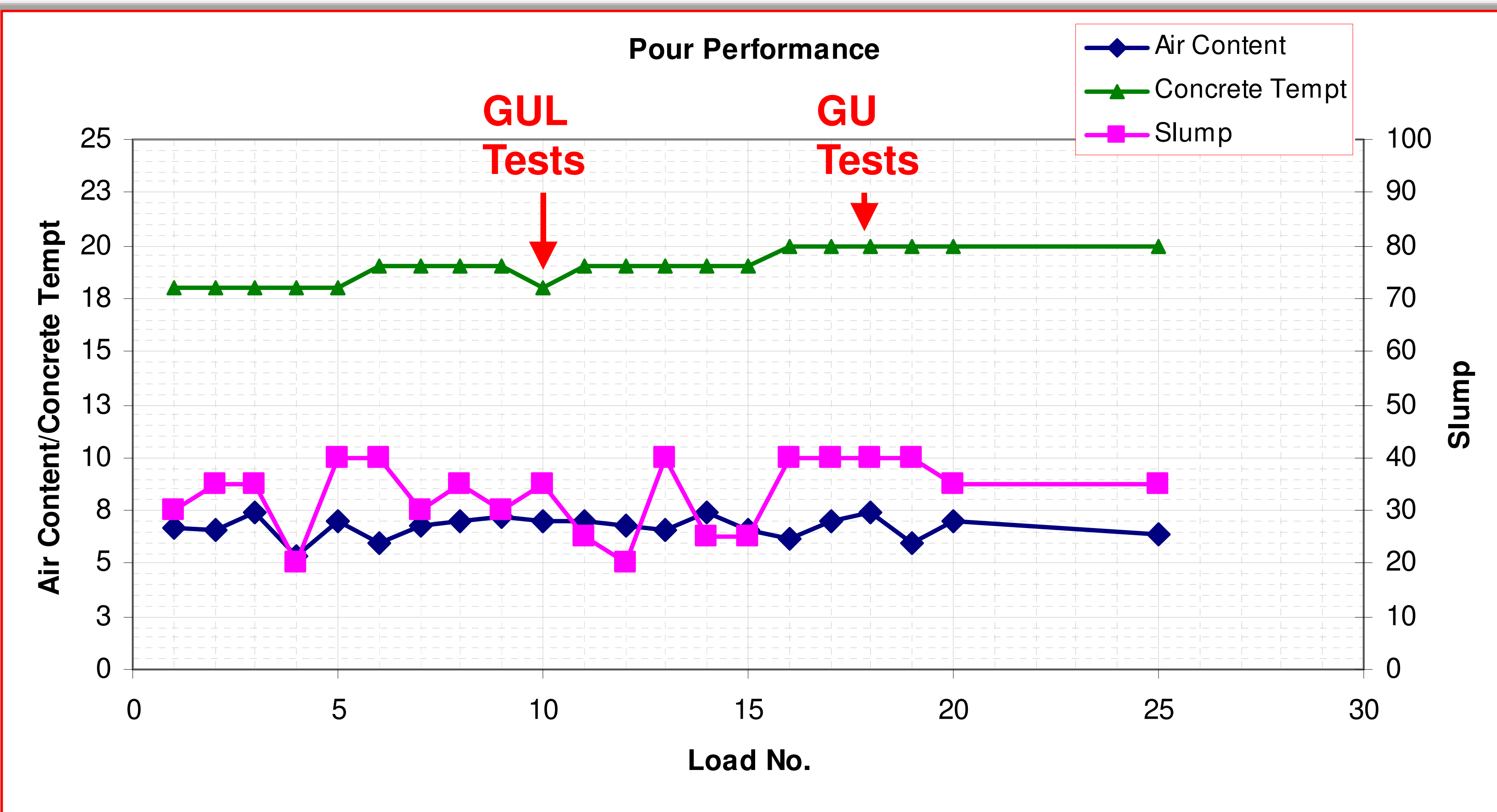
Concrete Plant

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

PLC (GUL) Test Section

Floating and Tyning

Test Data by Truck Load



Hardened Tests taken from Indicated 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 **56d** **99d**	**835** **702** **660**	**985** **770** **677**
(cored 150x300mm cyl.) **28d** **56d**	 **1215** **812**	 **1254** **794**
Cores from Pavement 28d **99d**	**2009** **972**	**2261** **983**
LS-435 28d shrinkage (%)	**0.023**	**0.022**

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

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/m2)	0.88	1.37

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 is being exposed to salt splash.

St. Marys Barrier Wall, Nov. 2011

Slip Formed Barrier Wall Data

	GU + Slag	GUL + 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 on saw cut slabs (kg/m^2)	0.25 (35 cycles)	0.09 (35 cycles)

3. Strengths of Air-entrained Concretes cured at 23 ^{o}C 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 Control	**89***	0.4	**39.3**	**45.5**	**50.7**	**52.6**
GU + 40% Slag	**53**	0.4	**32.8**	**46.2**	**49.2**	**51.2**
GUL9 + 40% Slag	**50**	0.4	**36.1**	**50.9**	**53.6**	**50.7**
GUL9 + 50% Slag	**41**	0.4	**34.6**	**49.0**	**53.0**	**51.0**
GUL15 + 40% Slag	**46**	0.4	**37.1**	**52.3**	**57.5**	**59.2**
GUL15 + 50% Slag	**38**	0.4	**36.3**	**55.3**	**60.1**	**65.6**
GUL15+ 6% Silica Fume + 25% Slag	**53**	0.4	**46.0**	**65.0**	**70.1**	**76.0**

*** 3.5% limestone and 8% gypsum**

U of Toronto Field site

3. RCPT of Air-entrained Concretes cured at 23 °C with limestone and SCMs

Mix Identification (all 400 kg/m^3 (666 pcy mixes)	% clinker in binder	w/cm	Rapid Chloride Permeability (Coulombs)		
			28 day	**56 day**	**182 day**
GU Control	**89**	0.4	**2,384**	**2,042**	**1,192**
GU + 40% Slag	**53**	0.4	**800**	**766**	**510**
PLC 9% + 40% Slag	**50**	0.4	**867**	**693**	**499**
PLC 9% + 50% Slag	**41**	0.4	**625**	**553**	**419**
PLC 15% + 40% Slag	**46**	0.4	**749**	**581**	**441**
PLC 15% + 50% Slag	**38**	0.4	**525**	**438**	**347**
PLC 15% + 6% Silica Fume + 25% Slag	**53**	0.4	**357**	**296**	**300**

Result of Highway Field Trials

- Based on their 3 winters of good performance in highway field trials, the MTO will allow 2 cement companies to use GUL portland-limestone cements on 2014 contracts in Ontario.
- The other cement companies will have to wait until they have 3-year field data (2015, 2016).

Over 100 miles of paving with PLC in Colorado and Utah with PLC supplied by Holcim (2007-2011)

Performance & Lower Environmental Impact

City of Denver Concrete Paving

- 40th & Havana (2007) - side by side comparison of ASTM C150 I/II (CSA GU) and ASTM C1157 GU cements (CSA GUL)
  - 20% Class C fly ash
  - No noticeable performance differences
  - Winter construction
- Holly Street - Ready-mix concrete supply (2008)
  - 25% Class C fly ash

City of Denver Concrete Paving 40th & Havana and Holly Street

US HW 287 Near Lamar, CO

US HW 287 Near Lamar, CO

- 7 Miles PCCP (2008)
  - Hot dry summer construction (~38C)
  - Designed for Heavy truck traffic
- 20% Class F fly ash
- 4.8 MPa average 28-day flexural strength
- Contractor received quality incentive per CDOT specifications
- Now used in concrete paving on a regular basis in Colorado

5. RCA replacing C.Agg. in Concrete Exposed to Freezing

Lab tests show poor F/T performance

	Control	15% RCA	25% RCA
Air (%)	5.9	5.3	5.4
28day (MPa) (psi)	44.9 6,500	44.7 6,480	41.2 5,975
C1202 (coulombs) 56d	910	1230	1330
C666 Durability Factor (%)	97.1	74.4	58.5
C672 Mass loss (kg/m^2)	0.21	0.29	0.25

But field performance is good after 2 winters

Therefore ASTM C666 Procedure A is not appropriate for evaluating RCA

Sidewalks placed Nov. 1, 2011 by Dufferin Concrete/Holcim

Recycling Toronto Pearson Airport Terminal 1 in 2004

Use of RCA as Granular Base at Toronto Pearson Airport

- All concrete from old terminals and aprons became RCA
- 145,000 T
- 0.5m [19 in.] thick granular base of RCA used under all new concrete aprons used up 75,000 T.
- Also saved ~4000 truck loads coming >50km (from quarry)

Concrete Mix Optimization to Reduce CO_2

Cause

Reduced paste fraction by:

- Optimization of Combined Aggregate Gradation
- Addition of Microfine Fillers to extend gradation

Reduced Portland cement content by:

- Addition of Interground Limestone
- Addition of Supplementary Cementitious Materials

Effect

Performance:

↑ Strength

Durability:

↓ Permeability

↓ Shrinkage

Sustainability :

↓ Cement content

Possible Cumulative reductions in Cement

(from 12% to 3% by volume) Anson-Cartwright & Hooton 2011

	Portland Cement	Water	Fine Aggregate	Coarse Aggregate	Air
Typical Concrete Bridge Deck Design	**12%**	14%	28%	40%	6%
Optimization of Combined Aggregate Gradation	**10%**	12%	30%	42%	6%
Addition of Microfine Fillers	**7%**	9%	32%	46%	6%
Addition of Interground Limestone	**6%** 1%	9%	32%	46%	6%
Addition of Supplementary Cementitious Materials	**3%** 1% 3%	9%	32%	46%	6%

Chart: % by Volume, Not To Scale

ie. From 380 kg/m^3 to 95 kg/m^3 (633pcf to 158 pcf) Cement

B: Durable Concrete is Sustainable Concrete

- Making durable concrete structures has a large impact on sustainability since times to rehabilitation and replacement can be extended.
- ie. Longer service life

Premature deterioration through inadequate design reduces concrete sustainability

Causes of Deterioration

Chemical

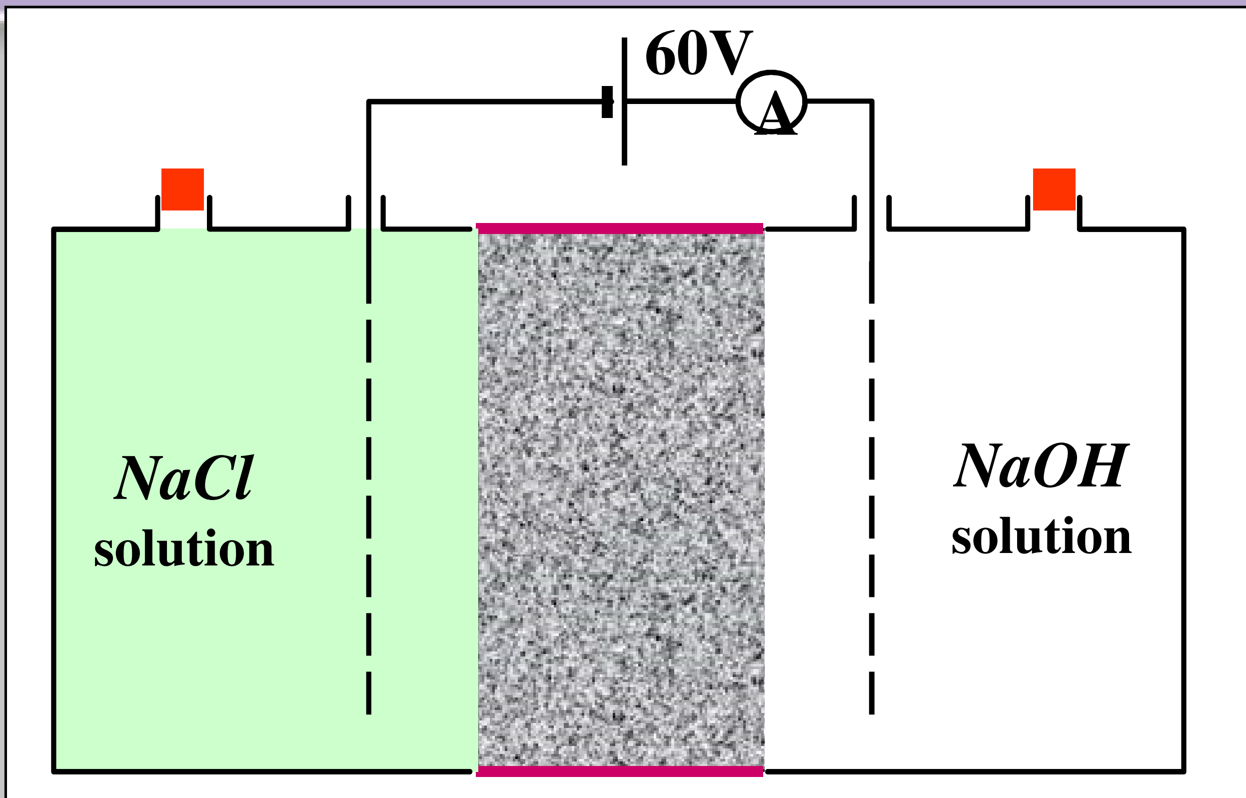
- Corrosion of steel
- Alkali-aggregate reaction
- Sulfate attack
- Acid attack

Physical

- Freeze/thaw (scaling)

All of these mechanisms involve water . . . and the rate at which they proceed is dependent on the ease with which water (and any dissolved salts) can move into or through the concrete pore structure

Rapid Chloride "Permeability" ASTM C1202



Voltage is applied and current passing through concrete is measured and integrated over 6 hours to get charge passed in Coulombs

A Rapid Index test for conductivity (connectivity) of the pore system. It does not measure permeability or chloride ingress. But it is a reasonable index test in most cases but there are easier methods to use.

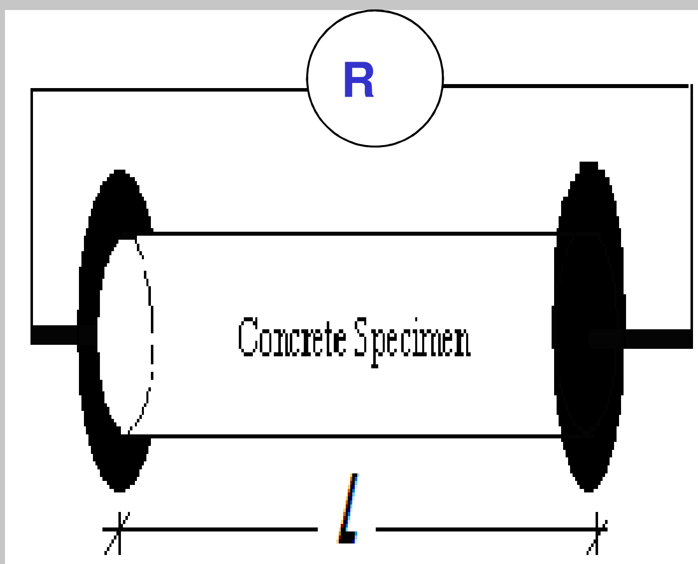
New Performance Tests

- The ASTM C1202 test is not as rapid or inexpensive as electrical resistivity tests.

- We are working on developing an ASTM standard for bulk resistivity, that may replace C1202.

Bulk Resistivity

- Simply measure the electric resistance through a wet concrete cylinder or core prior to strength tests

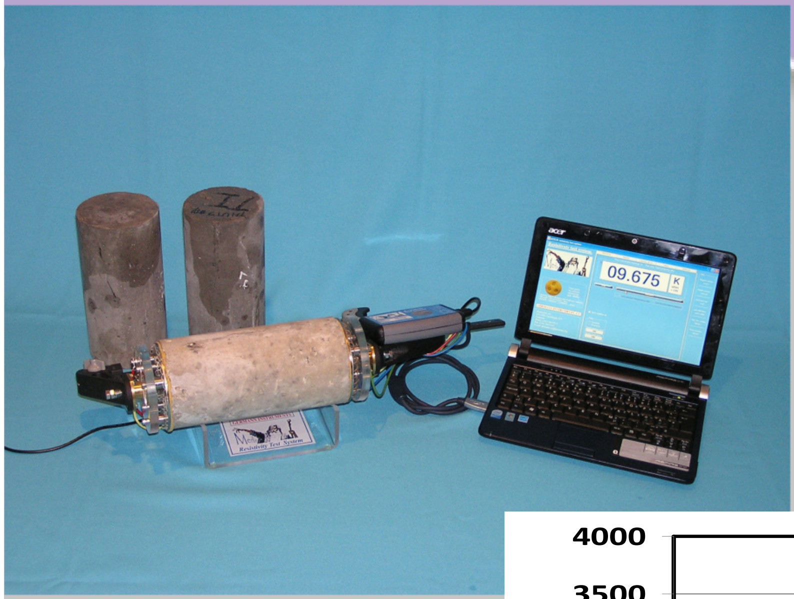


And calculate resistivity accounting for Area and Length of sample

$$\rho = R\,(A/L)$$

Various Commercial equipments are now available

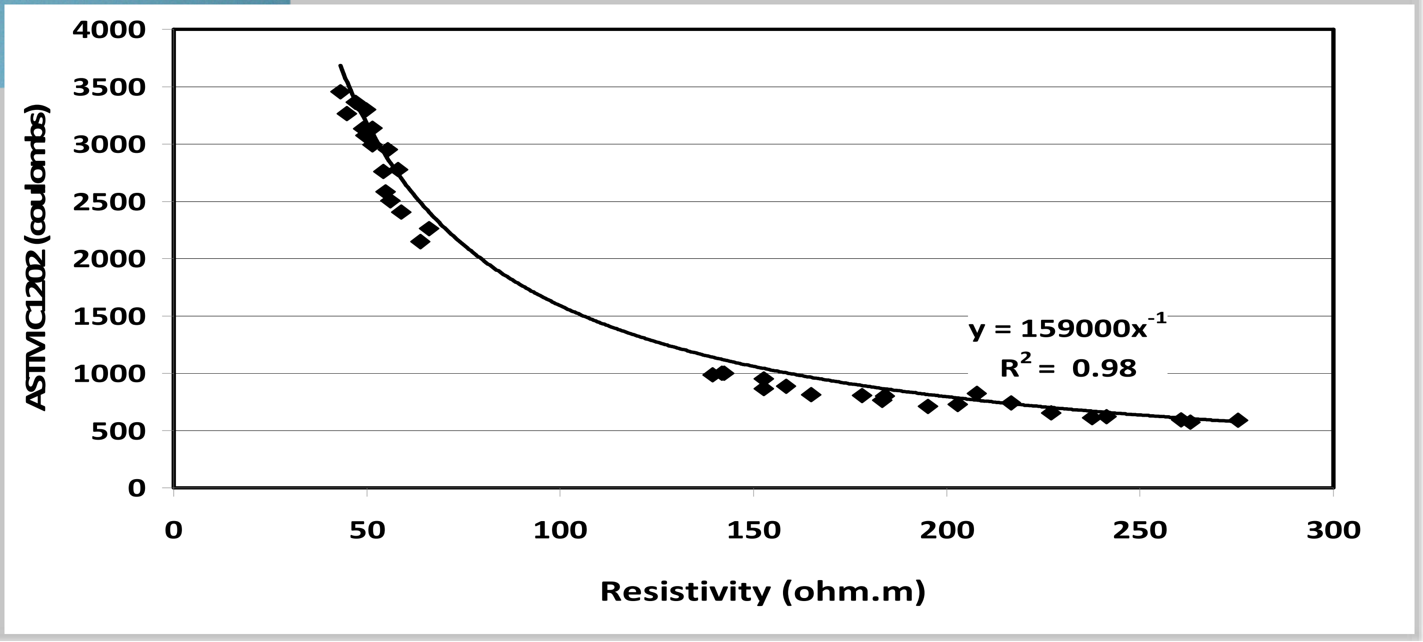
Bulk Resistivity Test vs ASTM C1202



The resistivity Test take less than 1 minute and the same sample can then be used for strength testing

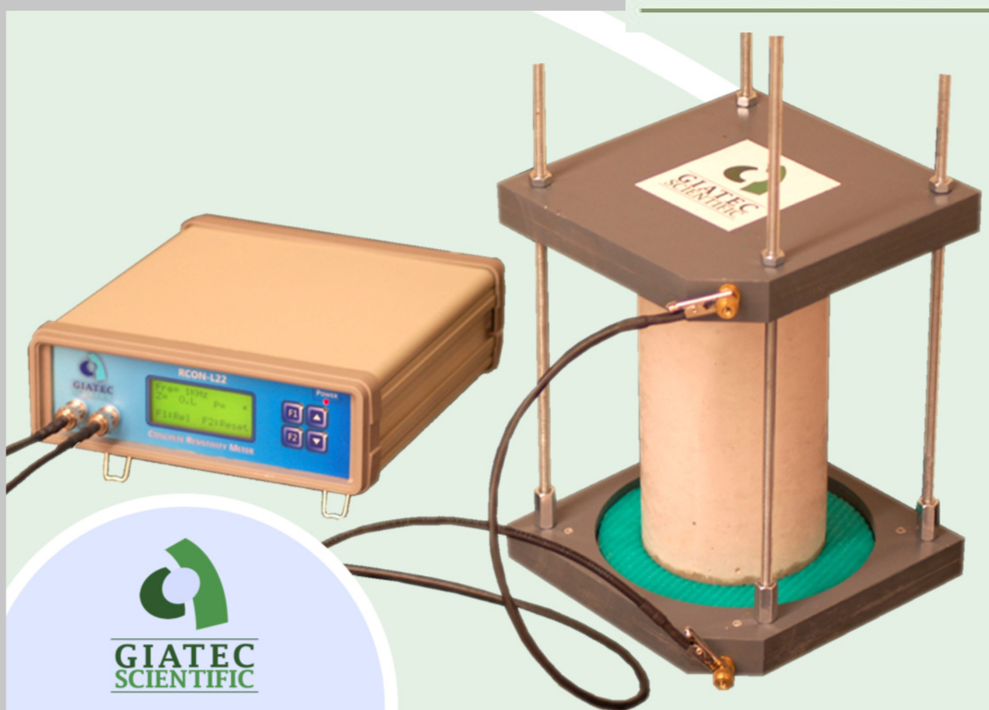
Germann "Merlin"

Uses fixed frequency of 325 Hz



Giatec RCon Bulk Resistivity Device

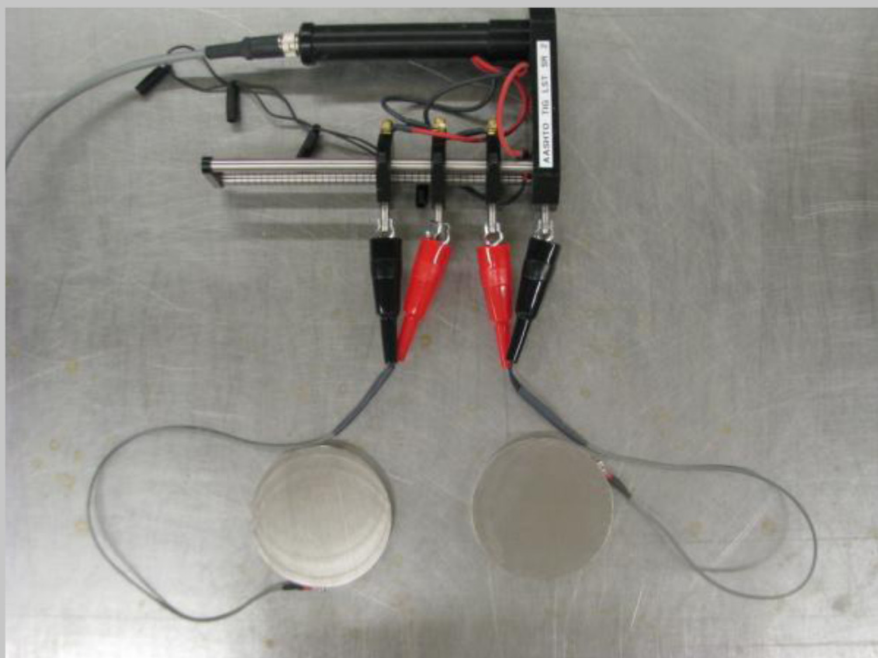
Reading Range	Frequency spectrum	Phase measurement
1 ~ 100 Ω	1Hz ~ 30KHz	0 ~ 180°
100 ~ 1000 Ω		
1 ~ 10 KΩ		
10 ~ 100 KΩ		
100 KΩ ~ 1 MΩ	1Hz ~ 10KHz	



Allows changing frequency to reduce impedance effects

Bulk AC Resistivity using Prosec Wenner Probe as Basis

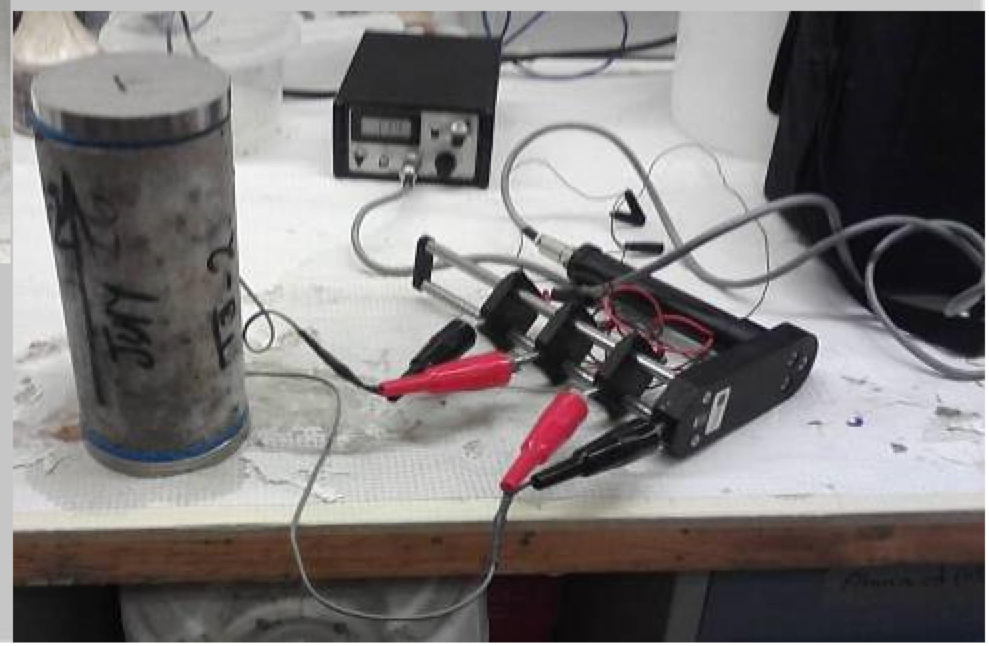
(J. Weiss Pooled Fund Study)



Wires from plates are attached to Wenner probe tips.

Wet sponges are used to make connections

$$\rho = R\frac{A}{L}$$



Specifying Durable Concrete

- Durability design includes more than the selection of concrete materials and mix proportions.
- Temperature control, adequate compaction, protection of fresh concrete, and curing need to be **detailed in the specification** and that **sufficient inspection and testing** be carried out to ensure that the specifications are being followed.
- Performance & objective-based specifications can improve the chances of obtaining of durability and allow more sustainable options
- What are the processes required to make successful durability-based performance specifications?

2010 *fib* Model Code being rolled out in Europe

- This new Code requires that structures be designed for durability to achieve a specified service life, in addition to structural strength and serviceability.
- The owner of the structure is provided with:

1. a *birth certificate* providing the design assumptions, as well as the specified and achieved properties, and

2. an *owner's maintenance manual* listing types and timing of required preventative maintenance, to avoid premature degradation.

What is a Performance Specification?

CSA A23.1 (Canada)

"A performance concrete specification is a method of specifying a construction product in which a final outcome is given in mandatory language, in a manner that the performance requirements can be measured by accepted industry standards and methods…."

What is a Performance Specification?

CSA A23.1(continued)

"The processes, materials, or activities used by the contractors, manufacturers, and materials suppliers are then left to their discretion."

CSA A23.1 adopted performance specifications in 2004 and made clarification revisions in 2009. Responsibilities of the Owner, the Contractor and the Concrete Supplier are clearly defined, including communication of problems and managing changes to rectify problems.

CSA A23.1 Performance Option

- The responsibilities of the owner, the supplier and the contractor are clearly defined in a Table with details provided in an Annex.
- For durability, CSA uses a table of exposure classifications to set the level of performance needed: Each exposure includes minimum requirements for concrete materials, properties and curing.

CSA A23.1-09 Exposure Classes

@ 56 days

Exposure Class	Max. W/CM	Specified strength (MPa) at age (days)	Air content %	Curing type	Cement Restriction (or use performance test)	ASTM C1202 Chloride resistance (coulombs)
C-XL	0.40	50 at 56 d	4-7 or 5-8% if frost exp.	Extended	-	<1000 at 56 d
					-	
C-1, A-1	0.40	35 at 28 d	4-7 or 5-8% if frost exp.	Additional	-	<1500 at 56 d
C-2, A-2	0.45	32 at 28 d	5-8%	Additional		
C-3, A-3	0.50	30 at 28 d	4-7%	Basic		
C-4, A-4	0.55	25 at 28 d	4-7%	Basic		
F-1	0.50	30 at 28 d	5-8%	Additional		
F-2	0.55	25 at 28 d	4-7%****	Basic		
N***	For design	For design	None	Basic		
S-1	0.40	35 at 56 d	4-5%	Additional	HS or HSb	
S-2	0.45	32 at 56 d	4-7%	Basic	HS or HSb	
S-3	0.50	30 at 56 d	4-7%	Basic	MS or MSb+	

This effectively requires SCMs in all concrete exposed to chlorides

Example Performance Spec. developed for a Subway Station

- Mass Concrete
- Below water table, so prevention of cracking is a performance requirement.
- Will not be in service for some time so 28 day requirements are not as important
- Strength of 35 MPa, air entrained, low-permeability

Performance Objectives

- First, the owner’s performance objectives need to be stated clearly and prioritized to develop an appropriate performance specification.
- Example: Owner wants leak-proof mass concrete for underground mass transit station. Also wants to meet CSA C-1 exposure, due to corrosion from tracked in salt and occasional freezing.

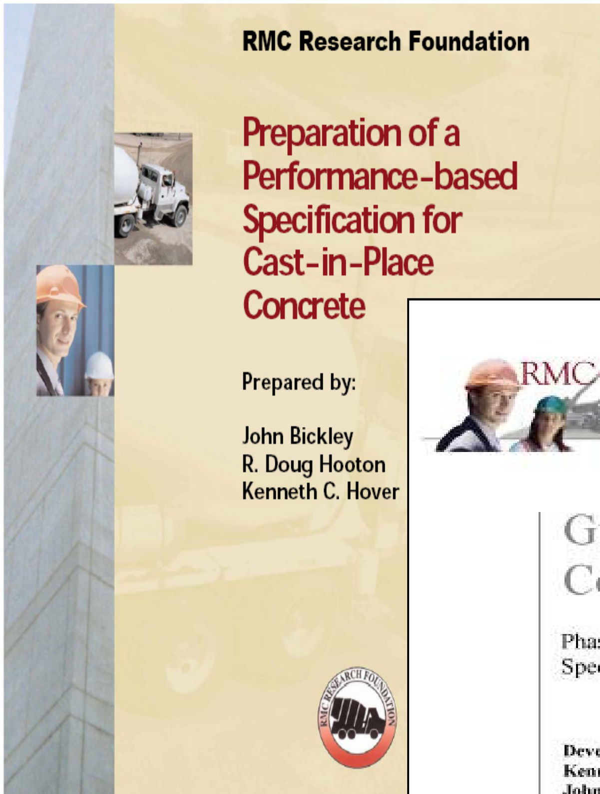
Write the Spec. to meet Objectives

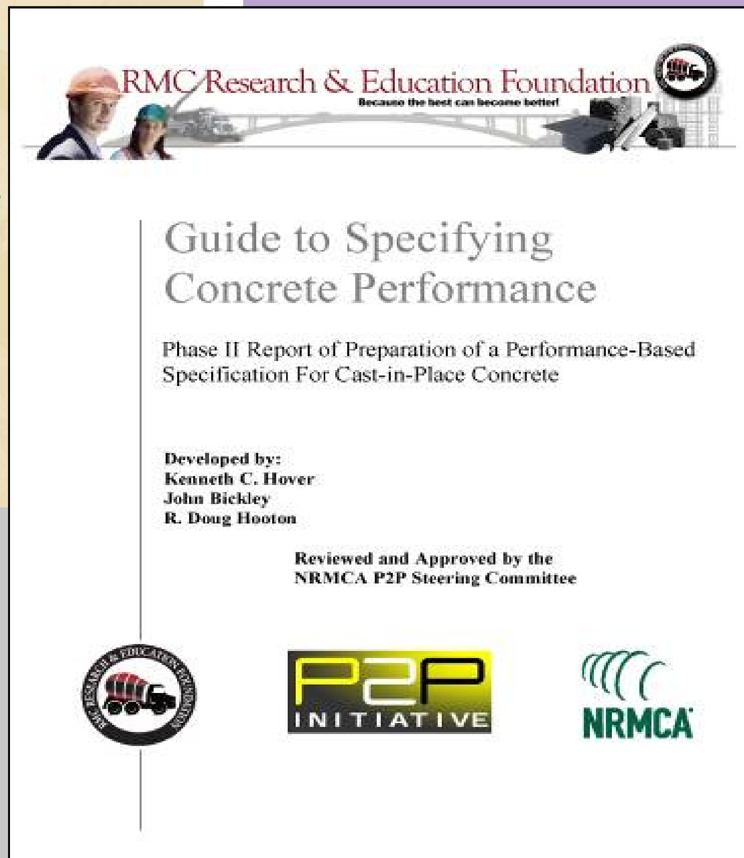
- Leakage is possible through the mass concrete, but far more likely through cracks and joints.
- So primary objectives are to design watertight joints and to minimize cracking (not to tell the supplier or the contractor how to make or place concrete).
  - Set max. temp. limits and max. differential temps
  - Set shrinkage limits
  - Set strength and permeability limits at 56 or 90 days
  - Allow relaxed w/cm limits if permeability limits can be met
  - Detail steel to minimize crack widths

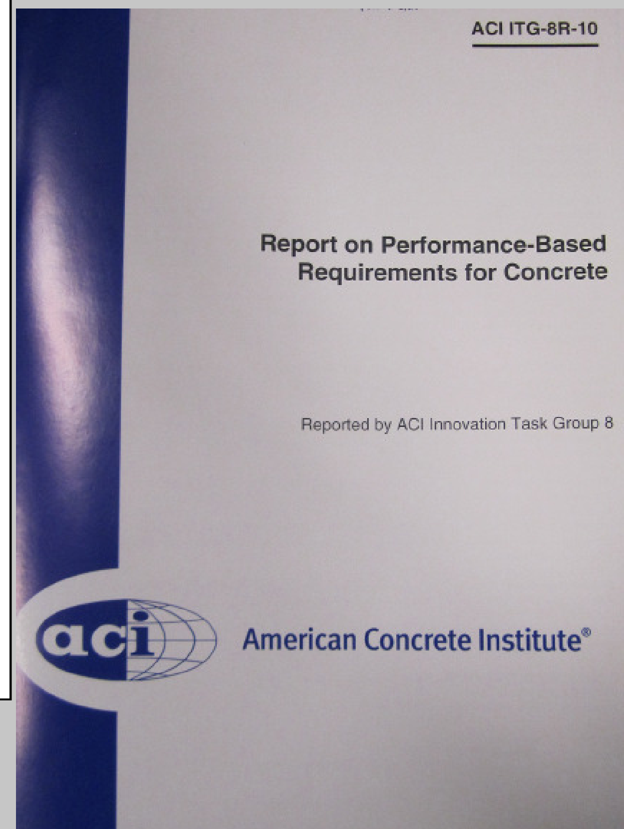
Owners Requirements

- The owner’s performance requirements were initially drafted by Bickley & Hooton for the Design Consultant.
- These also were based on previous experience in developing and implementing performance specs.

Background Documents







Web site: http://www.rmc-foundation.org

ACI Committee 329 is now working on alternative Performance Specifications

Specified In-place Strength

Compressive strength in-place:

29.8 MPa (0.85 x 35 MPa) at 91 days

(4,300 psi (0.85 x 5100 psi) at 91 days)

The longer time to reach specified strength allows the use of a mix with significant percentages of supplementary cementing materials resulting in less heat generation and lower thermal gradients

Specified Hardened Air Content

- Required minimum in-place air content = 3%
- Required average maximum in-place air-void spacing factor: 0.230 µm (0.009 in.) with no single value exceeding 260 µm (0.010 in.).
- *These criteria have been found to be adequate for freeze-thaw resistance.*

CHLORIDE RESISTANCE

Required maximum permeability index of x coulombs at 56 days using ASTM C 1202 as indicated in preconstruction tests to be consistent with meeting the maximum ASTM C1556 chloride diffusion coefficient: 3.0×10^{-12} m^2/s

This turned out to be ~1500 coulombs

CHLORIDE RESISTANCE
(COMMENTARY)

- *Determining chloride penetration resistance this by diffusion tests (needed for Service life modelling) is a lengthy business and not suited for acceptance purposes.*
- *Therefore determining a relationship between the ASTM C1202 test and a specified diffusion value was proposed.*
- *Future specs may use resistivity testing, once such tests have been standardized*

Drying Shrinkage

Maximum shrinkage of concrete prisms, determined after 7 days moist curing followed by 28 days of drying: 0.040%

-Following ASTM C157 test method

Also communicated that Lower shrinkage is desirable

Specified Temperature Max. & Gradients

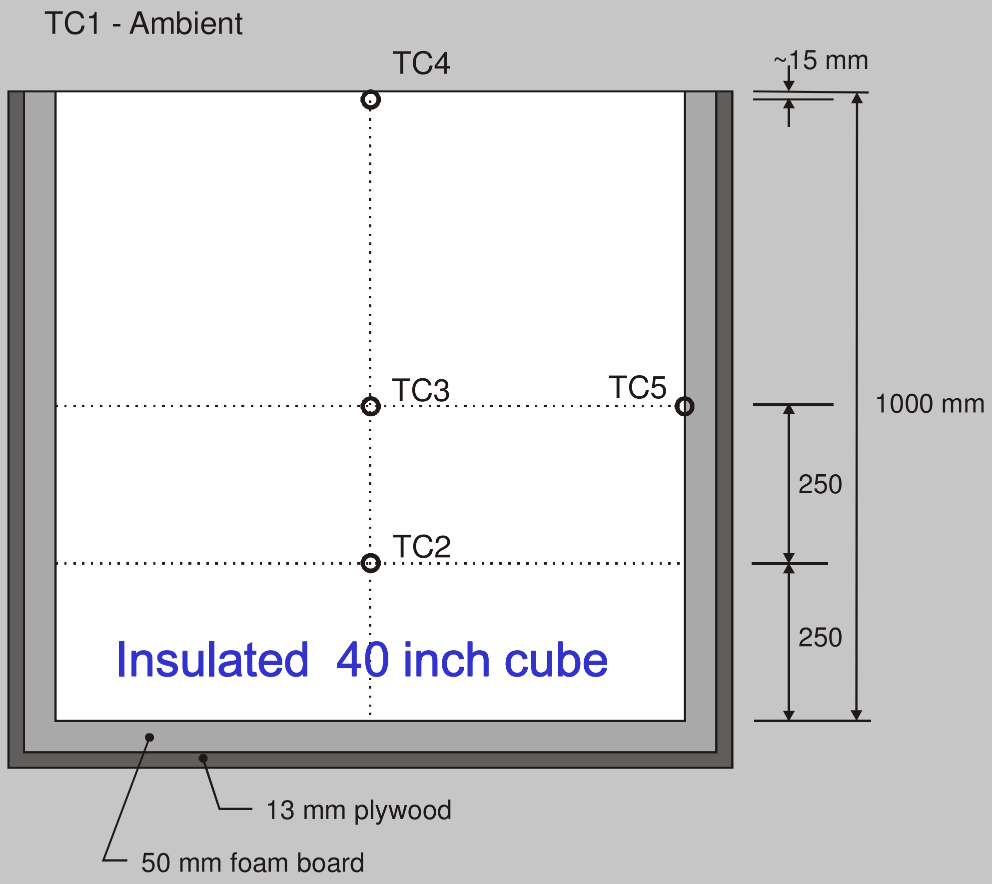
- The maximum temperature of the concrete in place shall not exceed 55^{o} C (141 ^{o}F) with a maximum allowable temperature gradient in any element of 20^{o}C (36 ^{o}F).
- In addition, the removal of forms shall not take place until the temperature gradient between the surface of the concrete and ambient complies with Table 21 of CSA A23.1.

THERMAL CRACK RESISTANCE
(COMMENTARY)

- *Meeting these criteria requires concrete mix designs that generate minimal heat during hydration.*
- *Typically these mixes are achieved using high-volume cement replacement with supplementary cementing materials.*
- *Also the controls of mixing and delivery temperatures need to be considered in the context of the time of the year that the concrete will be placed.*
- *The use of insulated formwork and extended times prior to formwork removal may be required.*

Spec. Requirements: Monolith Pre-Qualification Tests for Mass Concrete(results provided to owner)

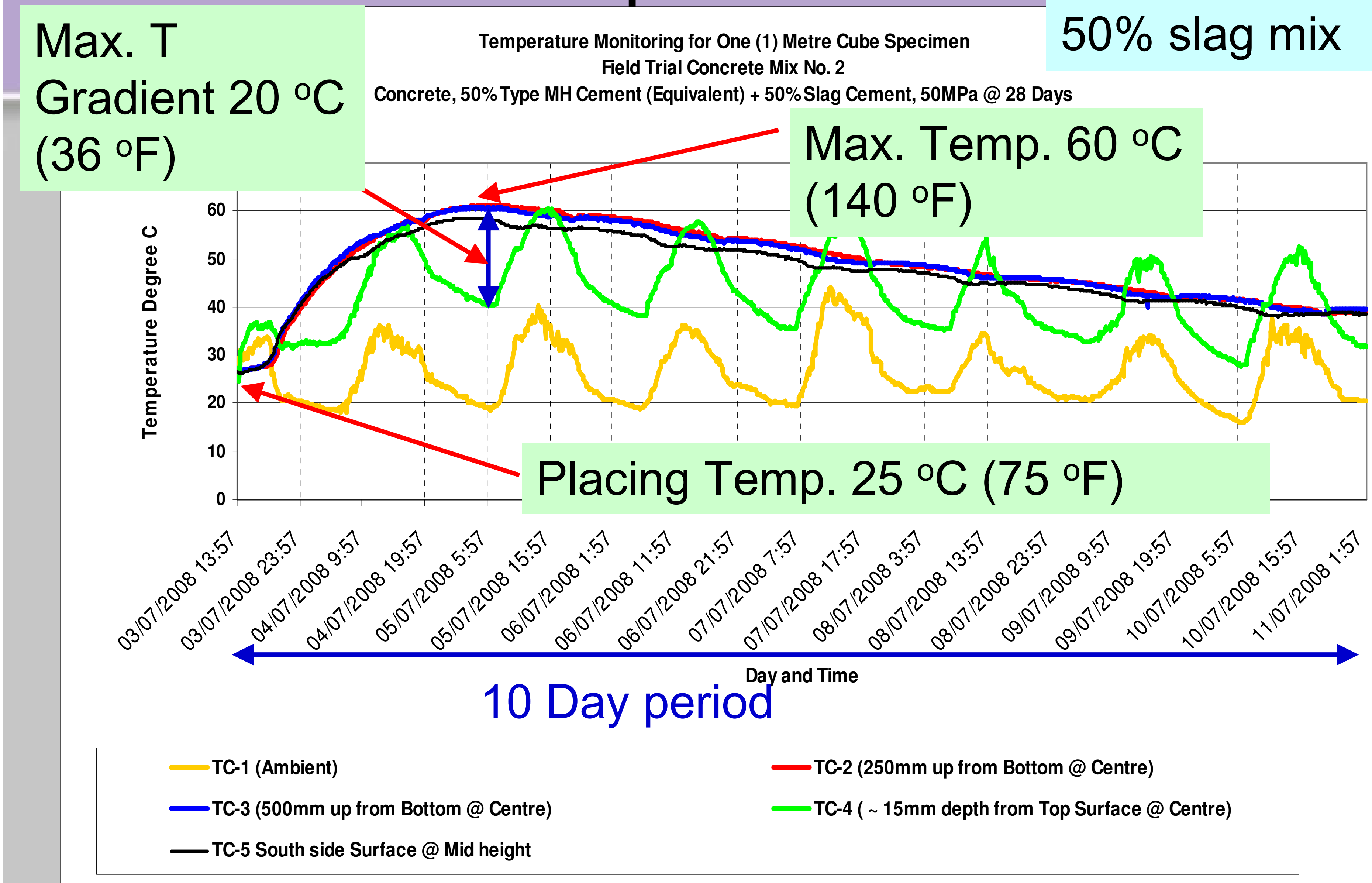
Concrete Suppliers must pre-qualify their Proposed Mixes using Monolith Tests and perform tests on cores from Block



Bickley & Hooton

Example 1m^3 (40 in. cube) Trial Temperatures

w/cm = 0.40, 50% slag mix



QUALITY CONTROL
(IN CSA PERFORMANCE SPEC.)

a) Is the responsibility of the Contractor

b) Tests strictly to correct procedures

c) Determine all specified properties and

d) Report results within 24 hours

e) Report problems and corrective actions immediately

f) Assist Owner if he/she wishes to make tests

CSA A23.1 Annex J: Contractor & Concrete Supplier Joint Responsibilities

"Since in a typical construction project the custody of the concrete transfers from the supplier to the contractor while in its plastic state, a high degree of coordination is required between supplier and contractor to ensure that the final product meets the performance criteria and that the quality control processes are compatible and demonstrate compliance."

CONTRACTOR PLUS CONCRETE SUPPLIER TEAM

a) Materials comply with relevant standards

b) Plant and Batcher certification

c) Preconstruction testing and recording

d) Determine Identity tests to be used on delivery

e) Perform monolith prequalification tests

f) Use certified testing laboratories

g) Wet curing mandatory

h) Forms and tarps remain till temperature gradient is low enough

2.2m thick (7.2 ft), 1200 m^3 (1570 yd3) Mass Slab Placement

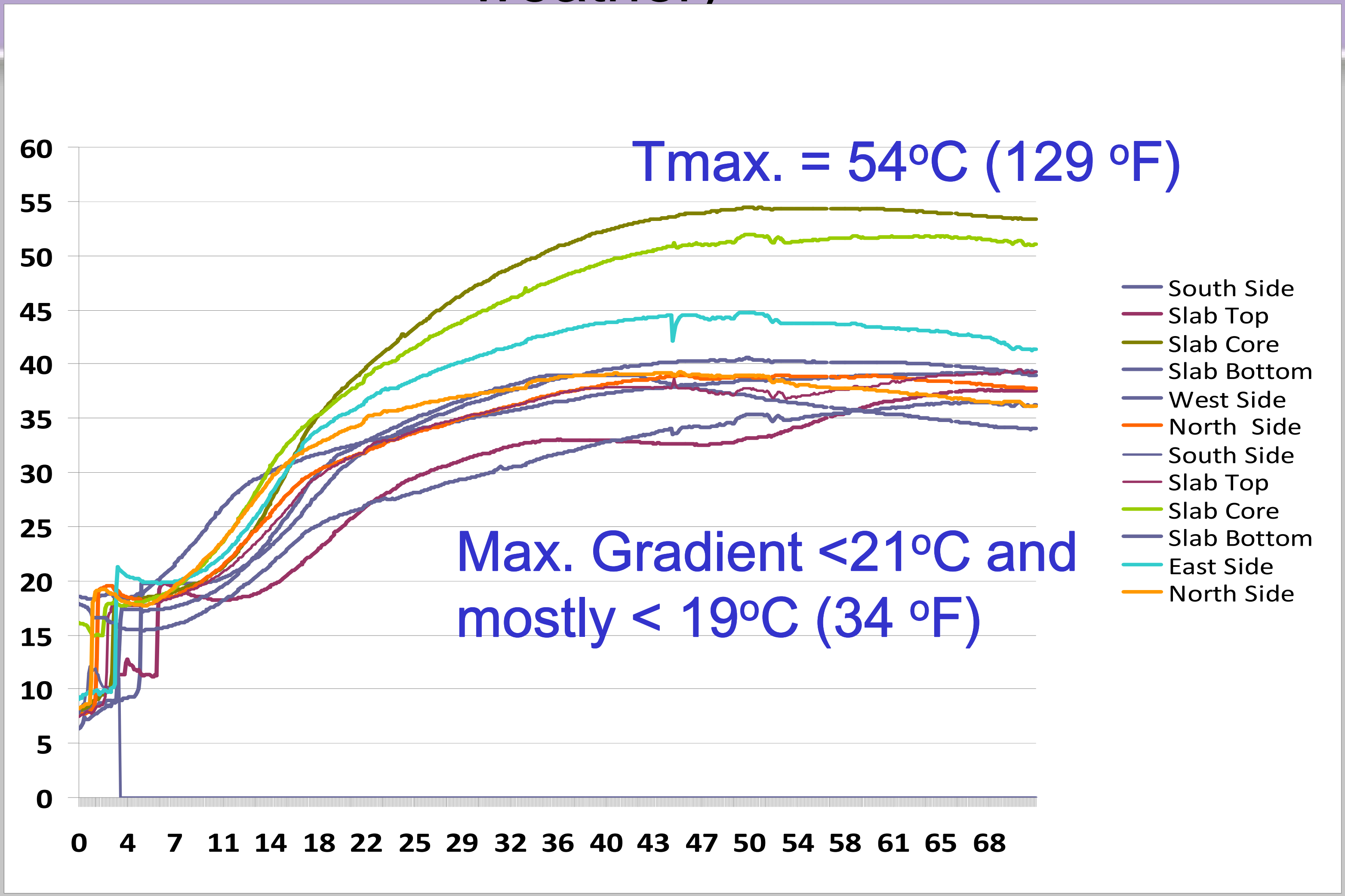
CSA C-1 mix (w/cm < 0.40, permeability index <1500 coulombs @ 56d)

with 125-160mm slump (5-7 in.) and 5-7% air.

- 49% slag (not 50%!)
- 40mm (1.5 in.) aggregate to help reduce heat.
- Top re-bars at 150 mm (6 in.) spacing.
- T.max. = 55^{o}C with max. gradient = 20^{o}C.

Slab Temperature Rise in 1st 72h
(concrete placed at <20^{o}C (68 ^{o}F) in 10^{o}C (50 ^{o}F) weather)

Temp. (^{o}C)



Time (hours)

Communication: Pre-Tender and Pre-Pour meetings

- A key to success of performance based projects is that the Contractors are aware of special provisions prior to bidding.
- Also, during construction, before each key concrete placement, a pre-pour meeting with suppliers, subcontractors and crews is needed to explain the objectives, ensure that adequate resources are in place, and that each party knows what needs to be done to ensure success.

Summary

- There are many changes that can be made to reduce the initial CO_2 footprint of concrete mixtures.
- We also need to design for durability to reduce the life-cycle CO_2 footprint of structures
- Performance specifications can increase the chances of obtaining durability and also provide the flexibility to use more sustainable concrete mixes

And lastly, we want “Greener” Concrete