Concrete is a Sustainable Material

- It uses local materials, uses less energy to produce than other materials, has long service life, and is recyclable.
- But, like with any construction material, the manufacturing and construction practices can be improved to reduce energy consumption and green house gas emissions.
Sustainability and Resilience

Concrete Structures are also Resilient

Resilience: the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to retain essentially the same function, structure, identity and feedbacks.

- Resilience is all about being able to overcome the unexpected. Sustainability is about survival. The goal of resilience is to thrive.

- Concrete buildings & infrastructure can survive extreme events

Resilience is the New Sustainability
Also, improving durability enhances sustainability

- Concrete can be **designed to be durable** even in aggressive environments.
- **Long-service life** means not having to replace buildings & infrastructure.
- Long-service life means not having to close down infrastructure as often for repair or replacement.
- Long-service life also **lowers life cycle costs** and the intangible costs associated with user inconvenience (estimated to be 9x the actual cost).

Per kg, concrete has low embodied CO₂ and Energy

Hammond and Jones, University of Bath, UK  2011
But we use 20 Billion Tons of concrete per year so the CO₂ (5%) and Energy (3.8%) impact is large.

---

Construction vs Life-Cycle Embodied CO₂

- 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
Plain Portland Cement Concrete

Cement production accounts for approximately 5% of CO₂ globally … and approximately 2.8% of CO₂ emissions in Canada (Neitzert, 1997)

Calcination: $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \uparrow$ (gas)  
Energy: $\text{C} + \text{O}_2 \rightarrow \text{CO}_2 \uparrow$ (gas)

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

www.cement.ca
Portland Cement production in Canada is amongst the most energy efficient globally. (33% reduction from 1972)

- Dry-process kilns
- Suspension pre-heaters
- Flash calciners
- Using waste heat to heat raw materials
- Use of alternative fuels and raw materials

Source: D. Herfort, Aalborg Portland Canadian Cement Plants
But cement is only one component of concrete (10-15%)}

- ~90% of carbon footprint of concrete is from portland cement (assuming portland cement is used as the sole binder)
- So reducing the portland cement or “clinker content” in the binder, and reducing the total binder content will reduce CO$_2$

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

Optimized Mix
- Well-graded; plenty of intermediate particles
- Microfine fillers; plenty of <75μm particles
- ↓ void content
- ↓ paste fraction required
The gap resulting from separate standards for fine & coarse grading envelopes

The gap resulting from meeting separate fine & coarse grading envelopes

Filling this gap with 6 mm stone, allowed up to 16% reduction in cement content for equal w/cm & workability.

And the 6 mm stone had been wasted from production of coarse aggregate.

As a result of this work, CSA now has an option to allow optimised total aggregate gradations.
2. Supplementary Cementing Materials

What are SCMs?
Mainly industrial by-products with reactive alumina & silica that can partially replace portland cement

- Fly ash from Coal Power
- Iron blast-furnace slag
- Silica fume from silicon alloy furnaces
- Also Natural pozzolans
Use of Supplementary Cementing Materials (SCMs) contribute to Green Design

- As industrial by-products, their use as a partial replacement for portland cement does not contribute significantly to the embodied energy and CO₂ impacts of cement in concrete.
- Virgin material usage is reduced in the manufacture of concrete.
- Reduced landfill disposal and increased use of recovered industrial materials.
- SCMs improve concrete service life through greater concrete durability.

In Canada SCMs typically replace 20-25% of cement—but it can go much higher.

3. Portland-Limestone Cement

- In 2008, CSA A3000 introduced a new class of portland-limestone cements with up to 15% interground limestone.
- CSA A23.1 followed in 2009 (adopted in the Canadian and Provincial Building Codes in 2011).
- This will have a direct effect on reducing point-source CO₂ emissions at cement plants by ~10%.
- These cements have also been used in US using ASTM C1157.
- In 2012, ASTM C595 adopted 15% limestone as a new Type IL category.
Portland-Limestone Cements (PLC) in CSA Standards

- Changes to the A3000 Cementitious Materials standard in 2008 and to the A23.1 concrete standard in 2009 allow use of PLC
- NBCC Building Code was updated in 2010 to include these changes (Provincial Codes followed in 2010+11)
- The Industry has labeled PLC

Strengths of Air-entrained CSA C-1 Concretes
cured at 23 °C with limestone and SCMs

<table>
<thead>
<tr>
<th>Mix Identification (all 400 kg/m3 (666 pcy) mixes)</th>
<th>% clinker in binder</th>
<th>w/cm</th>
<th>Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 day</td>
</tr>
<tr>
<td>GU Control</td>
<td>89*</td>
<td>0.4</td>
<td>39.3</td>
</tr>
<tr>
<td>GU + 40% Slag</td>
<td>53</td>
<td>0.4</td>
<td>32.8</td>
</tr>
<tr>
<td>GUL9 + 40% Slag</td>
<td>50</td>
<td>0.4</td>
<td>36.1</td>
</tr>
<tr>
<td>GUL9 + 50% Slag</td>
<td>41</td>
<td>0.4</td>
<td>34.6</td>
</tr>
<tr>
<td>GUL15 + 40% Slag</td>
<td>46</td>
<td>0.4</td>
<td>37.1</td>
</tr>
<tr>
<td>GUL15 + 50% Slag</td>
<td>38</td>
<td>0.4</td>
<td>36.3</td>
</tr>
<tr>
<td>GUL15+ 6% Silica Fume + 25% Slag</td>
<td>53</td>
<td>0.4</td>
<td>46.0</td>
</tr>
</tbody>
</table>

* 3.5% limestone and 8% gypsum

U of Toronto Field site
### Strengths of Air-entrained CSA C-1 Concretes cured at 23 °C with limestone and SCMs

<table>
<thead>
<tr>
<th>Mix Identification (all 400 kg/m³ (666 pcy) mixes)</th>
<th>% clinker in binder</th>
<th>Compressive Strength (MPa)</th>
<th>7 day</th>
<th>28 day</th>
<th>56 day</th>
<th>182 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU Control</td>
<td>89*</td>
<td></td>
<td>39.3</td>
<td>45.5</td>
<td>50.7</td>
<td>52.6</td>
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<tr>
<td> • 204 kg/m³ reduction in cement clinker (= 204 kg/m³ reduction in CO₂) by combined use of Type GUL cement plus SCM compared with Type GU  • CO₂ reduced by &gt;1.5 tonnes per 8-m³ truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>GUL15 + 40% Slag</td>
<td>40</td>
<td></td>
<td>37.1</td>
<td>52.5</td>
<td>57.3</td>
<td>59.2</td>
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<tr>
<td>GUL15 + 50% Slag</td>
<td>38</td>
<td></td>
<td>36.3</td>
<td>55.3</td>
<td>60.1</td>
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<tr>
<td>GUL15 + 6% Silica Fume + 25% Slag</td>
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<td></td>
<td>46.0</td>
<td>65.0</td>
<td>70.1</td>
<td>76.0</td>
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<tr>
<td>* 3.5% limestone and 8% gypsum</td>
<td>U of Toronto Field site</td>
<td></td>
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</tbody>
</table>

### ASTM C1202 Permeability Index of Air-entrained Concretes cured at 23 °C with limestone and SCMs

<table>
<thead>
<tr>
<th>Mix Identification (all 400 kg/m³ (666 pcy) mixes)</th>
<th>% clinker in binder</th>
<th>Rapid Chloride Permeability (Coulombs)</th>
<th>28 day</th>
<th>56 day</th>
<th>182 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU Cement Control</td>
<td>89</td>
<td></td>
<td>2384</td>
<td>2042</td>
<td>1192</td>
</tr>
<tr>
<td>GU + 40% Slag</td>
<td>53</td>
<td></td>
<td>800</td>
<td>766</td>
<td>510</td>
</tr>
<tr>
<td>PLC 9% + 40% Slag</td>
<td>50</td>
<td></td>
<td>867</td>
<td>693</td>
<td>499</td>
</tr>
<tr>
<td>PLC 9% + 50% Slag</td>
<td>41</td>
<td></td>
<td>625</td>
<td>553</td>
<td>419</td>
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<tr>
<td>PLC 15% + 40% Slag</td>
<td>46</td>
<td></td>
<td>749</td>
<td>581</td>
<td>441</td>
</tr>
<tr>
<td>PLC 15% + 50% Slag</td>
<td>38</td>
<td></td>
<td>525</td>
<td>438</td>
<td>347</td>
</tr>
<tr>
<td>PLC 15% + 6% Silica Fume + 25% Slag</td>
<td>53</td>
<td></td>
<td>357</td>
<td>296</td>
<td>300</td>
</tr>
</tbody>
</table>
PLC Trial Barrier Walls on QEW
Nov. 4, 2009

23 m³ of each mix placed, 30 MPa, 60-100 mm (2.5-4 in.) slump

GU Cement + 25% Slag
GUL Cement + 25% Slag

Nov. 2009 MTO Barrier Wall

<table>
<thead>
<tr>
<th>2009 Barrier Wall</th>
<th>PC +25% SLAG</th>
<th>PLC + 25% SLAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrinkage (28d)</td>
<td>0.038%</td>
<td>0.038%</td>
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<tr>
<td>Strength (MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>9.5</td>
<td>10.3</td>
</tr>
<tr>
<td>3</td>
<td>19.3</td>
<td>19.4</td>
</tr>
<tr>
<td>7</td>
<td>25.6</td>
<td>26.8</td>
</tr>
<tr>
<td>28</td>
<td>36.9</td>
<td>37.9</td>
</tr>
<tr>
<td>56</td>
<td>38.9</td>
<td>38.0</td>
</tr>
<tr>
<td>91</td>
<td>40.7</td>
<td>40.2</td>
</tr>
<tr>
<td>Freeze/Thaw Durability</td>
<td>94%</td>
<td>94%</td>
</tr>
<tr>
<td>MTO LS-412 Scaling</td>
<td>0.24 kg/m²</td>
<td>0.24 kg/m²</td>
</tr>
<tr>
<td>RCP (Coulombs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 days</td>
<td>2070</td>
<td>1490</td>
</tr>
<tr>
<td>56 days</td>
<td>1930</td>
<td>1340</td>
</tr>
</tbody>
</table>
**Impact of Portland-Limestone Cement on Emissions in Canada**

Will decrease CO₂ by 900,000 tonnes a year

Equivalent to taking 172,000 cars off the road

Equivalent to planting 23 million trees

(Assuming an 80% market conversion to PLC)

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**Supersulfated Cements**

- Supersulfated cements, using ground granulated blast-furnace slag and calcium sulfate with only 2-5% Portland cement.
- Such cements were used in the 1950-1960s in Europe, especially for mass concrete applications, but their lower early-age strength gain limited their commercial application.
- Holcim in Belgium recently gained experience with a commercially available supersulfated cement called Cemroc that offers enhanced durability in aggressive chemical environments.
- This product is not currently available in North America.
Supersulfated Cements

- The main part of the initial study at U of T was to try and improve the early-age properties of supersulfated cements in order to widen its acceptance by the construction industry.
- It was found that the mixture composition for optimum early-age strength is sensitive to the chemical composition of the blast furnace slag used, especially the alumina content.
- The goal of this research was to analyze the influence of the alkaline activator (Portland cement) content on slag with different alumina contents.

Trial Supersulfated Cement Strengths (MPa) (with Low-alumina Slag)

- More cement → higher compressive strength
- Activator content is more important than CaSO$_4$ content
- Low compressive strength!
Use of Recycled Concrete Aggregate at Toronto’s Pearson Airport

- All concrete from old terminals and aprons became RCA
- **145,000 Tons**
- 0.5m [19 in.] thick granular base of RCA used under all new concrete aprons used up 75,000 Tons.
- Also saved ~4000 truck loads coming >50km (from quarry)
- Some also used in concrete sidewalks to replace Coarse Aggregate
Possible Cumulative reductions in Cement
(from 12% to 3% by volume) Anson-Cartwright & Hooton 2011

<table>
<thead>
<tr>
<th></th>
<th>Portland Cement</th>
<th>Water</th>
<th>Fine Aggregate</th>
<th>Coarse Aggregate</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Concrete</td>
<td>12%</td>
<td>14%</td>
<td>78%</td>
<td>4%</td>
<td>6%</td>
</tr>
<tr>
<td>Optimization of</td>
<td>10%</td>
<td>12%</td>
<td>30%</td>
<td>42%</td>
<td>6%</td>
</tr>
<tr>
<td>Combined Aggregate</td>
<td>7%</td>
<td>9%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
</tr>
<tr>
<td>Gradation</td>
<td>6%</td>
<td>1%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
</tr>
<tr>
<td>Addition of</td>
<td>8%</td>
<td>3%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
</tr>
<tr>
<td>Microfines Fillers</td>
<td>6%</td>
<td>5%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
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<tr>
<td>Addition of</td>
<td>3%</td>
<td>5%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
</tr>
<tr>
<td>Grounded Limestone</td>
<td>3%</td>
<td>5%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
</tr>
<tr>
<td>Addition of</td>
<td>1%</td>
<td>5%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
</tr>
<tr>
<td>Supplementary</td>
<td>1%</td>
<td>5%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
</tr>
<tr>
<td>Cementitious Materials</td>
<td>1%</td>
<td>5%</td>
<td>32%</td>
<td>46%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Chart: % by Volume, Not To Scale

ie. From 380 kg/m³ to 95 kg/m³ (633pcf to 158 pcf) Cement

Durable Concrete is more 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 improves sustainability
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 (CSA A23.1 has a Performance Option).

Summary

- While concrete structures & infrastructure are durable, resilient & sustainable over their life-cycle, there are many changes that can be made to reduce the initial CO₂ footprint of concrete mixtures.
- We also need to specify concretes that are designed for durability to reduce the life-cycle CO₂ footprint of structures.
- Performance specifications can increase the chances of obtaining durability and remove barriers to use of more sustainable concretes.