LCA of Concrete Structures

Erin Ashley, PhD, LEED AP
Sr. Director of Sustainable Construction
NRMCA

Outline
- Benefits of LCA
- Case Study 1: Concrete Beam vs. Steel Beam
- Case Study 2: Concrete Building vs. Steel Building
- Case Study 3: Concrete Highway vs. Asphalt Highway
- Future LCA Research: MIT Concrete Sustainability Hub

How Do You Measure Sustainability?
- Best Approach: Life Cycle Assessment
- LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service.

Two common measures of sustainability
- Energy Consumption
- Carbon Footprint

Other Aspects Of Sustainability
- Acid rain
- Carcinogens
- Land use
- Mineral depletion
- Ozone depletion
- Radiation
- Respiratory pollution
- Water pollution

Life Cycle Stages

The procedures of life cycle assessment (LCA) are part of the ISO 14000 environmental management standards. ISO 14000 defines four distinct phases:

1. Goal and Scope
2. Life Cycle Inventory Analysis
3. Life Cycle Impact Assessment
4. Interpretation

Source: ISO (1997)

Where is LCA?

- LEED
- Green Globes
- IgCC
- Incorporate partial LCA in some cases

LEED®

LEED Pilot Credit Library

Pilot Credit 1: Life Cycle Assessment (LCA) of Building Assemblies and Materials

This credit involves the use of an Environmental Impact Calculator & USGBC Cradle to Cradle which will be available for use by projects participating in the pilot. It is not available to public viewing at this time.

This credit is available for pilot testing by the following LEED project types:

- New Construction

IgCC

- International Green Construction Code (IgCC)
- Overlay code to the IBC
- Version 2 completed, Final in 2012

Optional LCA

1.1 Primary energy use
1.2 Global warming potential
1.3 Acidification potential
1.4 Eutrophication
1.5 Ozone depletion potential
1.6 Smog potential
Pros and Cons of LCA

Pros
- Pinpoints places where process improvements can yield environmental benefits
- Good communication tool for customers and employees: market advantage

Cons
- Extremely complex and expensive
- Lack/unreliable Life Cycle Inventory data
- Prioritization of impacts is subjective

Should we Conduct LCA for Every Product/Project?

- Probably Not Realistic

Alternative:
- Rating Systems
- Surrogates for LCA
- Identify Impacts
- Prioritize Impacts
- Identify Trade Offs

Selected LCA Literature

- Life Cycle Inventory of Portland Cement Concrete – Marceau, Nisbet and Van Geem
- Comparison of the Life Cycle Assessments of an Insulating Concrete Form House and a Wood Frame House – Marceau and Van Geem
- How Sustainable is Concrete – Struble and Godfrey
- Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings – Guggemos and Horvath
- A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy And Global Warming Potential – Athena Institute

LCA Case Studies

Case Study 1: Concrete Beam vs. Steel Beam
- Paper: How Sustainable is Concrete
- Determine if concrete is a sustainable housing material
- LCA for entire housing unit too complex
- Start with a simple reinforced concrete beam and steel I-beam

LCA Model

- Used Athena Institute software
- Compare impacts of “ordinary” concrete with that of concrete containing fly ash
- Compare environmental impacts of concrete with the impact of steel
**Boundaries**
- Necessary to consider all stages in the life of a material

**Concrete Beam**
- 0.3 m long x 0.15 m wide x 0.29 m deep
- Compressive strength = 30 MPa
- Mass = 31.5 kg
- 2 - 30 mm diameter reinforcing bars
- Tensile Strength = 415 MPa
- Mass = 3.5 kg

**Steel Beam**
- 0.3 m long x 0.10 m wide x 0.3 m deep
- Tensile strength = 250 Mpa
- Mass = 10.0 kg

**Functional Unit**
- Concrete Beam
- Steel Beam
- Same bending moment capacity = 0.10 MN.m

**Concrete Mix Designs**

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Amount (kg/m³ concrete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate</td>
<td>1092</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>722</td>
</tr>
<tr>
<td>Portland cement</td>
<td>350</td>
</tr>
<tr>
<td>Fly ash</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td>160</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Amount (kg/m³ concrete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate</td>
<td>1092</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>722</td>
</tr>
<tr>
<td>Portland cement</td>
<td>315</td>
</tr>
<tr>
<td>Fly ash</td>
<td>35 (10%)</td>
</tr>
<tr>
<td>Water</td>
<td>160</td>
</tr>
</tbody>
</table>

**Computing Environmental Impacts**
- Embodied energy from available data sources
- ATHENA™ life cycle software
- Uses an extensive LCI database
- Various aspects of the building design are input, including the specific construction materials.
- Any or all of the following are estimated:
  - Energy consumption
  - Solid waste
  - Air pollution
  - Water pollution
  - Global warming
  - Resource use.
Energy use in the production of Portland cement

<table>
<thead>
<tr>
<th>Production Step</th>
<th>Energy (MJ/kg cement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction of raw materials</td>
<td>0.044</td>
</tr>
<tr>
<td>Transportation of raw materials</td>
<td>0.089</td>
</tr>
<tr>
<td>Crushing and grinding of raw materials</td>
<td>0.386</td>
</tr>
<tr>
<td>Pyroprocessing</td>
<td>4.041</td>
</tr>
<tr>
<td>Grinding cement</td>
<td>0.188</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.882</strong></td>
</tr>
</tbody>
</table>

Energy Used in the Production of Concrete

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate</td>
<td>0.028</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>0.028</td>
</tr>
<tr>
<td>Portland cement</td>
<td>0.735</td>
</tr>
<tr>
<td>Water</td>
<td>0.000</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>0.102</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.893</strong>*</td>
</tr>
</tbody>
</table>

* Reduced to 0.83 MJ/kg for 10% fly ash mix

Energy Used in Production of Steel

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Energy (GJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>23.70*</td>
</tr>
</tbody>
</table>

* Value for cold rolled steel (reinforcing steel). This value would be higher for structural steel but was the only available value.

Embodied Energy

<table>
<thead>
<tr>
<th>Beam</th>
<th>Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>237</td>
</tr>
</tbody>
</table>

Environmental Impacts Using Athena Model

<table>
<thead>
<tr>
<th>Impact</th>
<th>Reinforced Concrete</th>
<th>Structural Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource use (kg)</td>
<td>48.85</td>
<td>18.69</td>
</tr>
<tr>
<td>Global warming potential (kg equivalent CO₂)</td>
<td>9.97</td>
<td>8.95</td>
</tr>
<tr>
<td>Water pollution index</td>
<td>0.34</td>
<td>0.98</td>
</tr>
<tr>
<td>Air pollution index</td>
<td>2.01</td>
<td>2.46</td>
</tr>
<tr>
<td>Solid waste (kg)</td>
<td>1.87</td>
<td>1.80</td>
</tr>
<tr>
<td>Energy (MJ)</td>
<td>140.18</td>
<td>229.69</td>
</tr>
</tbody>
</table>

Conclusion

- Concrete has less environmental impact than steel for the same engineering function
- More difficult to answer the broader question of whether concrete housing is sustainable
- That question requires that we weigh the environmental impact and economic cost of the structure against its social benefits
- Authors have found no absolute criteria on which to evaluate sustainability
Case Study 2
Concrete Building vs. Steel Building
- Paper: Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings
- Angela Acree Guggemos, Colorado State University
- Arpad Horvath, University of California, Berkeley
- Journal of Infrastructure Systems, ASCE, 2005

Goal and Scope
- Identify/quantify energy use and emissions during the construction phase
- Structural steel frame
- Cast-in-place concrete frame
- Put these environmental loadings in larger perspective of the overall life cycle
- Allow a decision maker to form objective comparison of the two building types

Boundaries

Functional Unit
- 4,400 m2, five story building
- Located in midwestern U.S.
- Concrete mat foundation
- Aluminum and glass curtain wall
- Built-up roof
Identical Exterior and Interior Finish

Steel and Concrete Frame

Construction Phase Impacts

Full Life-Cycle Impacts

Summary of Life-Cycle Inventories for Steel- and Concrete-frame Buildings

<table>
<thead>
<tr>
<th></th>
<th>Energy (10 TJ)</th>
<th>CO₂ (Gg)</th>
<th>CO (Mg)</th>
<th>NO₂ (Mg)</th>
<th>PM₁₀ (Mg)</th>
<th>SO₂ (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel-Frame Building</td>
<td>36</td>
<td>26</td>
<td>38</td>
<td>72</td>
<td>9</td>
<td>100</td>
</tr>
<tr>
<td>Concrete-Frame Building</td>
<td>36</td>
<td>26</td>
<td>34</td>
<td>76</td>
<td>9</td>
<td>98</td>
</tr>
</tbody>
</table>

Materials, Construction and End-of Life Phase Impacts

Energy Impacts

Comparison of Energy Impacts

Comparison of Materials, Construction, and End-of-life Phases
**Comparison with Other Studies**

<table>
<thead>
<tr>
<th>Comparison of Embodied Energy and Emission Values for Structural Frames (current study and Björklund et al., 1996)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong> (MJ/m²)</td>
</tr>
<tr>
<td>Steel frame with concrete slabs (current study)</td>
</tr>
<tr>
<td>Steel frame with hollow core slabs (Björklund 1996)</td>
</tr>
<tr>
<td>Cast-in-place concrete frame (current study)</td>
</tr>
<tr>
<td>Cast-in-place concrete frame (Björklund 1996)</td>
</tr>
</tbody>
</table>

**Case Study 3: Concrete Road vs. Asphalt Road**

- Report: A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential
- Conducted by Athena Institute
- For Cement Association of Canada, 2006

**Discussion**

- Total life-cycle energy use and emissions for steel and concrete framed buildings are comparable
- Extra energy and emissions spent manufacturing the structural steel
- Extra energy and emissions used to construct and demolish concrete frame
- Large use-phase environmental effects dwarf every other life-cycle stage

**Goal and Scope**

- Compare the life cycle impacts of concrete highways vs. asphalt highways
- Limited to life cycle inventory analysis of:
  - Embodied primary (fossil) energy
  - Greenhouse gas emissions
- Does not include operational considerations
  - Energy use by cars and trucks
  - Lighting in urban areas

**Discussion (cont’d)**

- Construction phase small part (0.4–11%) of the overall building life-cycle energy use and emissions
- Maintenance and end-of-life phases have small total energy use and emissions
- The building use phase contributes the most energy-use impacts

**Goal and Scope (cont’d)**

- Several road types:
  - Canadian average arterial roads and high volume freeways
  - Quebec urban freeway
  - Section of Highway 401 freeway in Ontario
Boundaries

- Sub-grade and finished surface, including asphalt paved shoulders
- Excluded clearing, sub-grade, lane divider painting, etc.
- AASHTO Guide for Design of Pavement Structures & CAC method for rigid pavements
- 50 year study period captures major rehabs

Results: Embodied Energy for Canadian Arterial Highway

<table>
<thead>
<tr>
<th></th>
<th>Primary Energy</th>
<th>Feedstock Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC CBR 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC CBR 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC CBR 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC CBR 8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Functional Unit

- Road systems in Canada:

  Arterial Road  High Volume Highways

Results: Embodied Energy for Canadian High Volume Highway

<table>
<thead>
<tr>
<th></th>
<th>Primary Energy</th>
<th>Feedstock Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC CBR 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC CBR 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC CBR 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC CBR 8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Definitions

- Feedstock Energy
  - The gross combustion heat value of any fossil hydrocarbon material input to a product system which is an energy source, but is not being used as an energy source (e.g., bitumen) including its related pre-combustion energy.
- Embodied Primary Energy
  - Sum of primary energy and feedstock energy.

Results: Global Warming Potential for Canadian Arterial and High Volume Highways

<table>
<thead>
<tr>
<th></th>
<th>Asphalt</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial CBR 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arterial CBR 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. Vol. CBR 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. Vol CBR 8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Truck Energy Use

- National Resources Council of Canada
- Compared fuel consumption and emissions for major urban arterial highway
- One paved with asphalt, other with concrete

Average Savings 3.85%

<table>
<thead>
<tr>
<th>Fuel Savings</th>
<th>18,130 l/km (7,708 gal/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 Reductions</td>
<td>50 t/km (88 tons/mi)</td>
</tr>
</tbody>
</table>

Truck Energy Use (cont’d)

- Trucks traveling on concrete
- Fuel savings average 3.85%
- Reductions in GWP
- Concrete pavement stiffer than asphalt
- Less rolling resistance

Car Energy Use

- University of Texas at Arlington Study
- Investigated differences in fuel consumption and CO2 emissions
- Operating automobile on asphalt pavement versus a concrete pavement under city driving conditions
- Driving on concrete pavements can reduce fuel consumption by 3% to 17% fuel savings

Car Energy Use (cont’d)

- Example for Dallas-Fort Worth, Texas
- If cars travelled at constant speed of 50 km/h (30 mph) on concrete pavements similar to those in the study
- Annual fuel savings
  - 670 million liters (177 million gallons)
- Annual CO2 reduction
  - 620,000 tonnes (680,000 tons)

Lighting

- Concrete pavements can also reduce energy demand for lighting
- Concrete is more reflective
- Fewer lighting fixtures are needed to provide the same illumination on a roadway built with concrete instead of asphalt.
- An report by Richard Stark demonstrated 31% less energy

Future LCA Research: MIT Sustainability Hub
**CSH R&D Platforms**

**Concrete Sciences**
- Scientific breakthroughs towards reducing the CO2 footprint of Cement & Concrete

**Building Technology**
- The CO2 Mileage of concrete structures
- Material Flow
- Life Cycle Analysis of Pavement and Buildings

**Econometrics**
- Impact on economy
- Job creation
- System Dynamics
- Input - Output
- Effect of policy (e.g. Carbon Tax)

**Goals**
- Identify areas in which concrete excels compared to other materials
- Identify opportunities for improvements
- Create solid technical basis for future industry development

**Building Technology Platform**
- Mission: Life Cycle Assessment (LCA) of concrete buildings and pavements to identify impacts and opportunities

**Research Topics:**
- Material Flow Analysis
- LCA of buildings
- LCA of pavements

**Material Flow Analysis**

**Life Cycle Analysis of Buildings**
- Thermal performance of various concrete assemblies, with an emphasis on role of thermal mass in reducing operating energy
- Residential and commercial
- The heat island effect will be considered according to the reflectivity of different materials
- Carbon accounting in the built environment

**LCA of Pavements**
- Construction and maintenance embodied energy
- Traffic emissions during maintenance
- Fuel efficiency for semi-trucks and passenger vehicles
- Material and aggregate consumption
- Impact of heat island effect
- Fossil fuel consumption
MIT Concrete Sustainability Hub

- $10 million investment over next 5 years
- Funded equally by RMCREF & PCA
- NRMCA providing technical support and guidance
- NRMCA and state associations to play a critical role in the technology transfer

U.S. Carbon Emissions

Initial MIT CSH Work Plans

- Work Plans for the First Two Years Have Been Approved and are Underway
  - The Edge of Concrete: A Life-Cycle Investigation of Concrete and Concrete Structures
  - From Liquid to Stone: The Genesis of Concrete

August Deliverables - Buildings

- Life Cycle Assessment of Single-Family Residential Homes
  - Air-infiltration tests of about 20 US ICF homes
  - LCA results for ICF versus stick-frame homes for 2 climatic zones (Phoenix and Chicago)
  - Life cycle carbon emissions for construction, maintenance and use

Life Cycle Analysis of Buildings

- Thermal performance of various concrete assemblies, using data from real buildings where possible
- Residential and commercial
- Acoustical performance and indoor air quality will be compared across building types
- The heat island effect will be considered according to the reflectivity of different materials
- Carbon accounting in the built environment

August Deliverables - Buildings

- “For residential buildings, ICF construction can offer HVAC energy savings of 30 percent compared to code compliant wood-framed buildings in a cold climate like Chicago. Such operational energy savings can compensate for the initial carbon emissions of the concrete within a few decades of operation.”
August Deliverables - Buildings

- Life Cycle Assessment of Multi-Family Residential Homes
  - LCA results for ICF, CMU and steel frame buildings
  - Four-story building (12,000 sf) in 3 climatic zones (Miami, Phoenix & Chicago)
  - Life cycle carbon emissions for construction, maintenance and use

Life Cycle Analysis of Pavements

- Construction and maintenance embodied energy
- Traffic emissions during maintenance
- Fuel efficiency for semi-trucks and passenger vehicle
- Material and aggregate consumption
- Impact of heat island effect
- Fossil fuel consumption

Methodology

Life Cycle Assessment framework:
- System boundary definition
- Inventory
  - Inputs – energy and materials needs
  - Outputs – waste and emissions
- Impact Assessment
  - Global Warming Potential in CO₂e
- Interpretation of the results

Functional Unit:
- 1 m² of paved surface with 50 year lifetime

Software: GaBi 4 by PE International + US Construction database

August Deliverables - Buildings

- Life Cycle Assessment of Commercial Buildings
  - LCA results for reinforced concrete and steel frame construction for a Department of Energy (DOE) benchmark office building
  - 12-story building (460,000 sf) in 2 climatic zones (Phoenix and Chicago)
  - Life cycle carbon emissions for construction, maintenance and use

August Deliverables - Pavements

- Assessment of fuel consumption for highway pavements
- LCA results for a range of pavement designs
- Life cycle carbon emission for construction, maintenance and use
  - Running behind on life cycle economic costs – more to come later this fall

“For commercial buildings, the higher thermal mass of concrete buildings can offer savings of 6 percent of the HVAC energy consumption for a hot climate such as Phoenix, and 5 percent of HVAC energy for a cold climate such as Chicago, when compared to steel construction.”

“Even greater reductions of 25 percent (or more) of HVAC energy are possible through improved design of concrete commercial buildings.”
Rolling Resistance

The largest known life cycle GHG contribution
Two effects: Pavement structure and pavement roughness

![Figure 3. Illustration of asphalt (left) and concrete pavement rolling resistance](Source: Santero, et al. 2009)

August Deliverables – Pavements

- "For a high traffic volume highway, the greater fuel efficiency of vehicles driving on concrete pavements can lead to significantly lower carbon emissions compared to an asphalt pavement. Over a 50-year lifetime, the savings could be as high as 80 percent of the carbon emissions associated with pavement selection."
- "For a moderate volume highway, the savings are approximately 60 percent of carbon emissions over a 50-year lifetime."

Concrete Science Platform

- Research Topics – “Cracking the DNA Code of Concrete”
  - Dissolution of Clinker Phases
  - Precipitation of Calcium-Silica-Hydrates (C-S-H)
  - Cohesion, Setting, Micro-Texture Development
  - Model Validation Tools

August Deliverables - Concrete Science Platform

- Interim Progress in All Phases with Final Work to Be Completed in November 2012
- New Test Methods – Fracture Testing
- Enrich Existing Models like the Virtual Cement & Concrete Testing Lab (VCCTL) at NIST
- Added Credibility; Recognition World-Wide
- Will Influence LCA Model / Future Quantification

Concrete Science Platform

- Mission: Scientific breakthroughs toward reducing CO₂ footprint of cement and concrete
  - Strength with Less Material
  - Lower Energy Processing
  - Chemical Stability
- Work can make concrete more sustainable into the future, further influencing the LCA work

MIT CSH Governance & Future Work

- Research Board – Power to approve work plans and direction of the CSH – 2 sponsors, 2 MIT, requires unanimous approval to move forward
- MIT Industry Advisory Council – 8 industry representatives, 4 “concrete” and 4 “cement”
- RMCREF & PCA Boards
- NRMCA Committees; RMCREF Advisory Council
NRMCA Leadership

- Feedback on work plans; Participation in task groups; Keeping abreast of related research
- NRMCA committees and state/allied associations are starting to develop recommendations for coordinated implementation of the results
- Ideas for future areas of study – e.g. environmental impact of truck weight restrictions, concrete’s disaster resistance benefits, illumination aspects

Concrete Sustainability Hub at MIT

- Major industry investment with long-term implications for the industry and nation
- Huge opportunity to quantify sustainable advantages of concrete and identify areas for improvement from THE most credible independent source
- Societal Value: Make the most sustainable building product even MORE sustainable

Questions