LCA of Concrete Structures

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

Other Aspects Of Sustainability

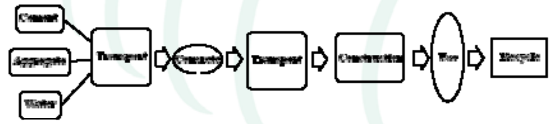
- Acid rain
- Carcinogens
- Land use
- Mineral depletion
- Ozone depletion
- Radiation
- Respiratory pollution
- Water pollution

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?

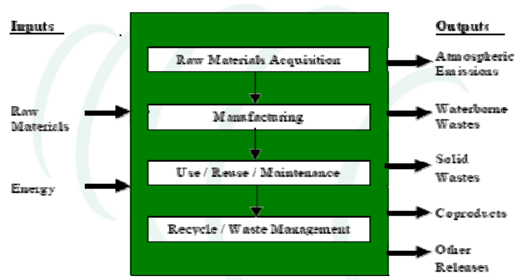
- Best Approach: Life Cycle Assessment
- LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service.



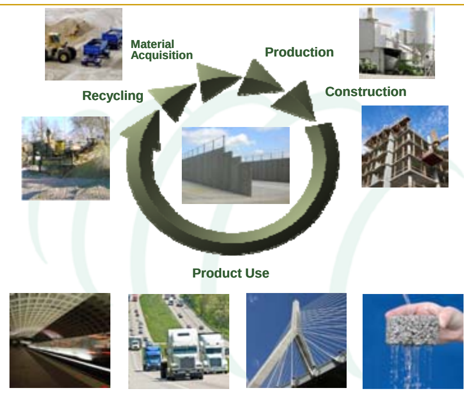
Two common measures of sustainability

- Energy Consumption
- Carbon Footprint

Life Cycle Stages



Source: EPA (2003)



Where is LCA

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

International Standards Organization (ISO)

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

LEED®

LEED Pilot Credit Library

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

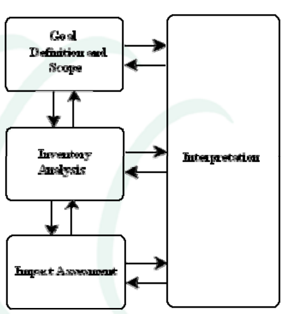
This credit involves the use of an Environmental Impact Calculator & USGBC Credit Calculator which will be available for use by projects participating in the pilot. It is not available for public viewing at this time.

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

- New Construction

Four phases of performing a LCA

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



Source: ISO (1997)

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

LCA Case Studies

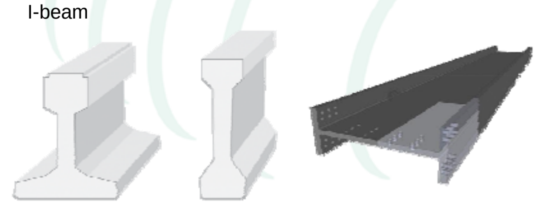
NRMCA

Should we Conduct LCA for Every Product/Project?

- Probably Not Realistic
- Alternative:
  - Rating Systems
  - Surrogates for LCA
  - Identify Impacts
  - Prioritize Impacts
  - Identify Trade Offs

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



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 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

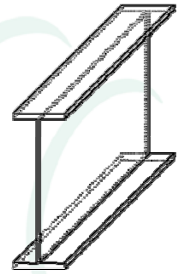
ATHENA Impact Estimator for buildings

Boundaries

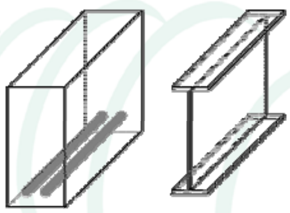
- Necessary to consider all stages in the life of a material

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

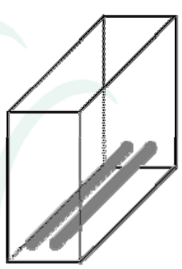
Concrete Mix Designs

Constituents	Amount (kg/m3 concrete)
Coarse aggregate	1092
Fine aggregate	722
Portland cement	350
Fly ash	0
Water	160

Constituents	Amount (kg/m3 concrete)
Coarse aggregate	1092
Fine aggregate	722
Portland cement	315
Fly ash	35 (10%)
Water	160

Concrete Beam

- 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



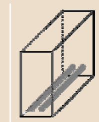
Computing Environmental Impacts

- 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

Production Step	Energy (MJ/kg cement)
Extraction of raw materials	0.044
Transportation of raw materials	0.089
Crushing and grinding of raw materials	0.386
Pyroprocessing	4.041
Grinding cement	0.188
Total	4.882

Embodied Energy

Beam	Energy (MJ)
	109
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Energy Used in the Production of Concrete

Constituents	Energy (MJ/kg)
Coarse aggregate	0.028
Fine aggregate	0.028
Portland cement	0.735
Water	0.000
Manufacturing	0.102
Total	0.893*

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

Environmental Impacts Using Athena Model

Impact	Reinforced Concrete	Structural Steel
Resource use (kg)	48.85	18.69
Global warming potential (kg equivalent CO_2)	9.97	8.95
Water pollution index	0.34	0.98
Air pollution index	2.01	2.46
Solid waste (kg)	1.87	1.80
Energy (MJ)	140.18	229.69

Energy Used in Production of Steel

Constituent	Energy (GJ/kg)
Steel	23.70*

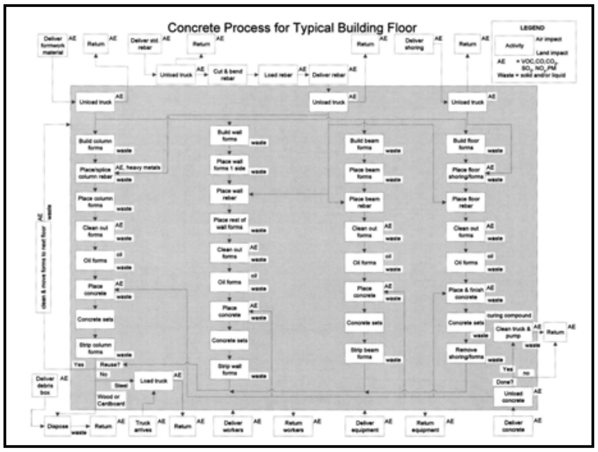
* Value for cold rolled steel (reinforcing steel). This value would be higher for structural steel but was the only available value.

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

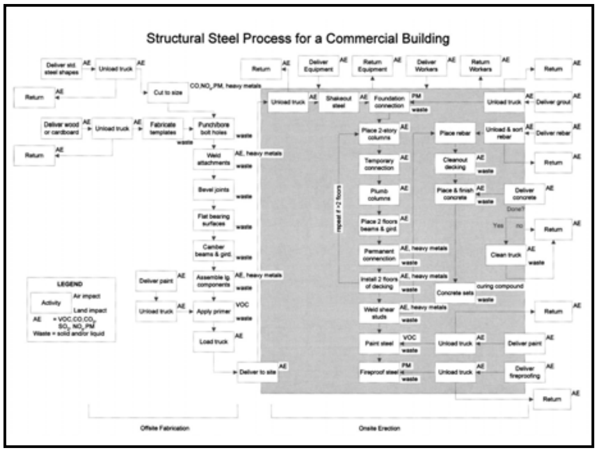
Case Study 2
Concrete Building vs. Steel Building

- 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

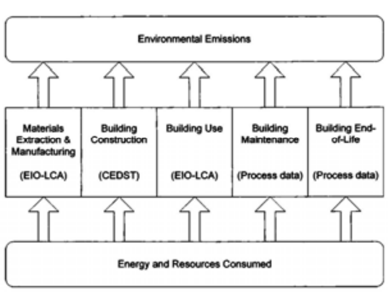


Goal and Scope

- 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

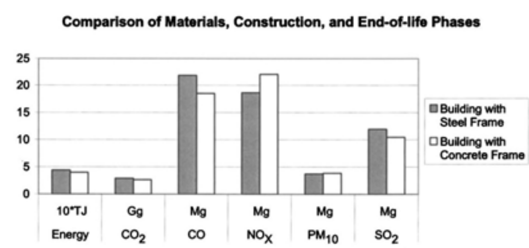
Full Life-Cycle Impacts

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

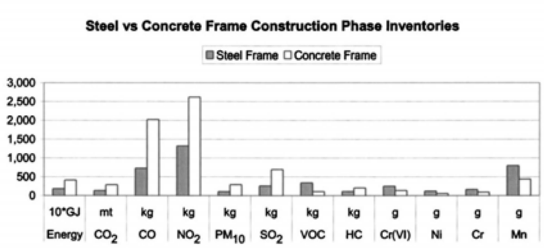
	Energy (10 TJ)	CO_2 (Gg)	CO (Mg)	NO_x (Mg)	PM_{10} (Mg)	SO_2 (Mg)
Steel-Frame Building	36	26	38	72	9	100
Concrete-Frame Building	36	26	34	76	9	98

Steel and Concrete Frame

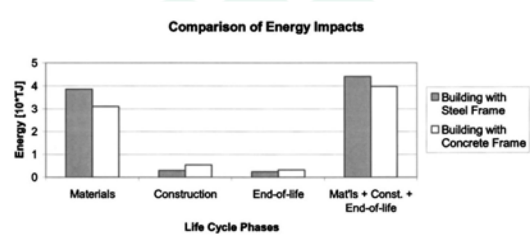
Materials, Construction and End-of Life Phase Impacts



Construction Phase Impacts



Energy Impacts



Comparison with Other Studies

Comparison of Embodied Energy and Emission Values for Structural Frames (current study and Björklund et al., 1996)				
	Energy (MJ/m2)	CO2 (kg/m2)	NOx (kg/m2)	SOx (kg/m2)
Steel frame with concrete slabs (current study)	9,500	620	3.2	2.7
Steel frame with hollow core slabs (Bjorkland 1996)	912	87	0.49	0.16
Cast-in-place concrete frame (current study)	8,300	550	3.7	2.3
Cast-in-place concrete frame (Bjorkland 1996)	1,190	128	0.53	0.15

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

Functional Unit

- Road systems in Canada:

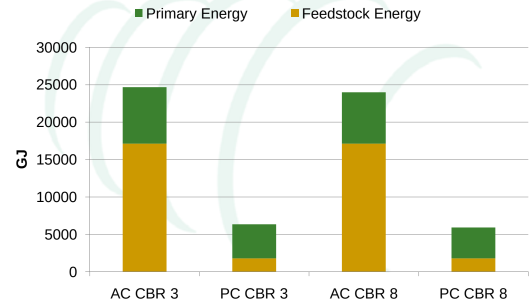
Arterial Road

High Volume Highways

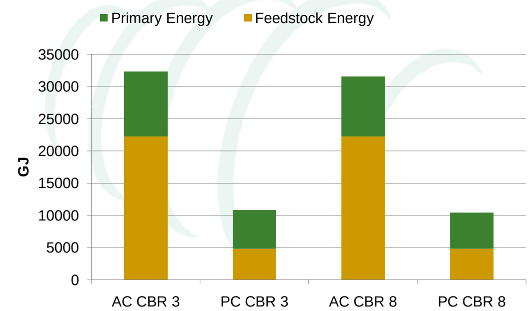
Definitions

- 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.

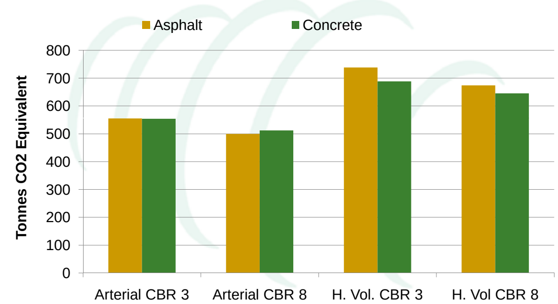
Results: Embodied Energy for Canadian Arterial Highway



Results: Embodied Energy for Canadian High Volume Highway

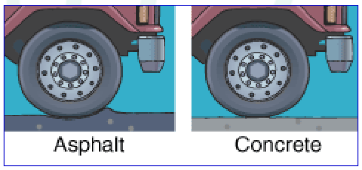


Results: Global Warming Potential for Canadian Arterial and High Volume Highways



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



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

Average Savings 3.85%	
Fuel Savings	18,130 l/ km (7,708 gal/mi)
CO_2 Reductions	50 t/ km (88 tons/mi)

Car Energy Use

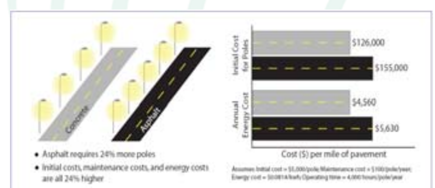
- University of Texas at Arlington Study
- Investigated differences in fuel consumption and CO_2 emissions
- Operating automobile on asphalt pavement versus a concrete pavement under city driving conditions
- Driving on concrete pavements can reduce fuel consumption by 3% to 17% fuel savings

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 CO_2 reduction
  - 620,000 tonnes (680,000 tons)
-

Lighting

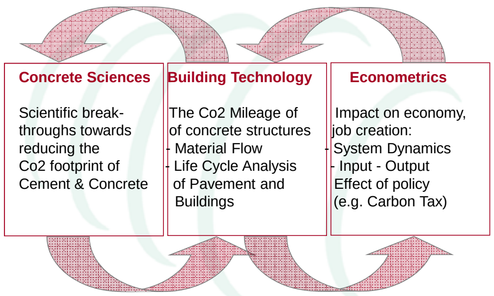
- Concrete pavements can also reduce energy demand for lighting
- Concrete is more reflective
- Fewer lighting fixtures are needed to provide the same illumination on a roadway built with concrete instead of asphalt.
- An report by Richard Stark demonstrated 31% less energy



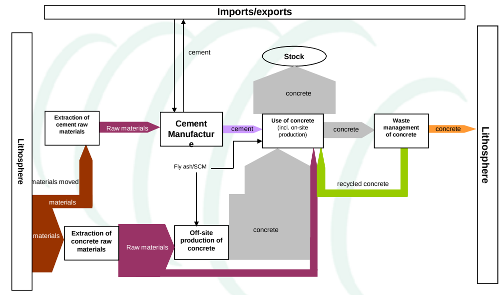
Future LCA Research: MIT Sustainability Hub

NRMCA

CSH R&D Platforms



Material Flow Analysis



Goals

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

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

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

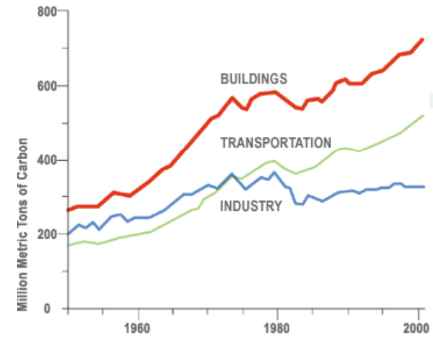
LCA of Pavements

- 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



(Source: DOE)

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

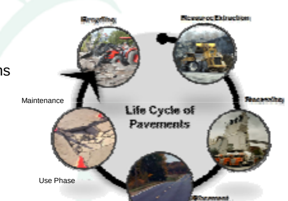
August Deliverables - Buildings

- 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

Methodology

Life Cycle Assessment framework:

- System boundary definition
- Inventory
  - Inputs – energy and materials needs
  - Outputs – waste and emissions
- Impact Assessment
  - Global Warming Potential in CO_2e
- Interpretation of the results



LCA Boundaries

No capital goods

Functional Unit:

- 1 m² of paved surface with 50 year lifetime

Software: GaBi 4 by PE International + US Construction database

August Deliverables - Buildings

- *"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."*

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*

Rolling Resistance

The largest known life cycle GHG contribution

Two effects: Pavement structure and pavement roughness

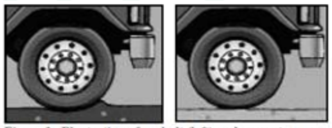


Figure 3. Illustration of asphalt (left) and concrete pavement rolling resistance

Source: Santero, et al. 2009

Parameters
Pavement type Traffic volume Traffic composition Base fuel efficiency Temperature etc.

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

NRMCA

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 compare 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."*

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 CO_2 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

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