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GREEN DESIGN FOR MOVABLE BRIDGES

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TOP TEN STRATEGIES FOR GREEN BRIDGE DESIGN

Design bridges that encourage or accommodate public transportation, pedestrians, bicycles, car pools, and low-emitting vehicles.

Use recycled materials and industrial by-products. Concrete with fly ash content of 50% replacement for Portland cement has been successfully used on major bridges.

Minimize maintenance costs. Consider weathering steel to eliminate painting.

Divert construction waste from landfills.

Perform a Life Cycle Cost Analysis to compare the proposed design alternatives. Note – This has been a Federal requirement since 2005.

Perform a Life Cycle Assessment to compare the carbon footprint, pollution, embodied energy, and economic activity associated with each proposed design alternative. The free software at www.eiolca.net is recommended.

Use construction equipment that meets modern emissions standards.

Use regionally extracted and manufactured materials.

Use grid-source green electricity.

Innovate.

Abstract

The goal of green design includes reducing greenhouse gas emissions, pollution emissions, waste, and the use of non-renewable resources to sustainable levels. The recently published Transportation Research Board "Special Report 290" concluded that climate change "will have significant impacts on transportation, affecting the way US transportation professionals plan, design, construct, operate, and maintain infrastructure" and "is not just a problem for the future."

There is no existing standard for the green design of bridges or transportation infrastructure. Bridge professionals need not wait for this void to be filled. Green design strategies are well established and can be applied to projects immediately. The LEED Green Building Rating System™ was created for commercial buildings, but includes many provisions that are applicable to bridge projects. See Table 1.

Adopting life cycle thinking is perhaps the single most effective measure bridge engineers can take towards achieving green designs. This approach involves considering all stages of a bridge's life: raw material acquisition, transportation, fabrication, use, maintenance, and salvage/disposal. Life cycle thinking is applied in two distinct regimes, life cycle cost analysis and life cycle assessment.

Life cycle cost analysis is used to evaluate alternative designs based on lowest total cost, instead of merely lowest construction cost. This total life cycle cost includes agency, user, and vulnerability costs. Since 2005, this analysis has been mandated for federally funded bridge projects over twenty million dollars. BrideLCC software, developed with federal funding, is available free on-line. It costs money to damage the environment. Decreasing total life cycle costs will tend to decrease environmental damage.

Life cycle assessment is the tool that is used to estimate carbon dioxide emissions, or "carbon footprint", of a product or service. The assessment can also estimate many other types of environmental impacts, including energy and material resource inputs, as well as waste and pollution outputs. An economic input-output approach to life cycle assessment, as used by the free internet based software www.eiolca.net, is well suited to comparing the environmental impacts of alternative bridge designs.

A literature review is provided in Appendix A to summarize several documents relevant to green design for bridges.

Purpose

The purpose of this paper is to recommend methods for reducing the environmental impact of movable bridges. This approach can be referred to as green design or sustainable design. The goal of green design includes reducing greenhouse gas (GHG) emissions, pollution emissions, waste, and use of non-renewable resources to sustainable levels. The Brundtlandt Commission, convened by the United Nations in 1983, defined that the goal of sustainable development is to "meet the needs of the present without compromising the ability of future generations to meet their own needs."

Impetus for Green Design

Green design is new terminology for bridge engineers; however most of its concepts are not new. Bridge engineers have a history of considering environmental concerns. Efficient resource use is integral to engineering design. New bridge construction is preceded by an environmental impact statement. Bridge projects comply with a myriad of environmental regulations. Green design also includes concepts that are new to bridge engineering, particularly the reduction of GHG emissions.

The Intergovernmental Panel on Climate Change (IPCC) was created by the United Nations in 1988 to provide an objective source of information about climate change. The IPCC shared the 2007 Nobel Peace Prize and their publications are considered authoritative. In November 2007 the IPCC published its Fourth Assessment Report which concluded: "Warming of the climate system is *unequivical* [100% certain]" and "Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* [>90%] due to observed increase in anthropogenic GHG concentrations."

In response to the IPCC findings the Transportation Research Board (TRB) published special report 290 "Potential Impacts of Climate Change on US Transportation" in cooperation with the US Department of Transportation, the Environmental Protection Agency, National Cooperative Highway Research Program, US Army Corps of Engineers, and the National Research Council. This report concluded that climate change "will have significant impacts on transportation, affecting the way US transportation professionals plan, design, construct, operate, and maintain infrastructure" and "is not just a problem for the future." The TRB 290 report focused on adaption strategies (such as designing for increased storm loads, sea level, and temperatures), it also recognized the importance of reducing transportation related GHG emissions.

Within the US, there is not yet a mandate to reduce GHG emissions. The current presidential candidates from both parties have sponsored a cap and trade bill to limit GHG emissions. More than 170 countries, including all developed countries except the US, have ratified the Kyoto Protocol and have accepted mandatory reductions of GHG emissions.

Architects and the building industry have recognized the utility and marketability of green design. The US Green Building Council (USGBC) created the LEED accreditation standards. Thousands of LEED accredited green buildings have been constructed. Customers for green buildings include not only private companies such as: Ford Motor Company, BP, and Turner Construction; but also twenty-eight state governments, including the Virginia DOT; twelve federal agencies such as: US Army, NASA, and Department of State; and many local government agencies such as: MTA Bridges and Tunnels and the Seattle DOT.

There is no existing standard for the green design of bridges or transportation infrastructure. It is inevitable that this void will soon be filled by AASHTO, USGBC, or another entity. Bridge professionals need not wait. Green design strategies are well established and can be applied to projects immediately.

LEED Accreditation

"The LEED (Leadership in Energy & Environmental Design) Green Building Rating System™ is a voluntary, consensus-based standard to support and certify successful green building design, construction and operations [www.usgbc.org]." The LEED for New Construction Version 2.2 standard has sixty-nine available points and seven prerequisites, a minimum of twenty-six points are required for a building to be certified as green. The points and prerequisites for LEED-NC Version 2.2 are organized into six broad categories: sustainable sites, water efficiency, energy & atmosphere, materials & resources, indoor environmental quality, and innovation & design process. Points that can be applied to bridge construction, either directly or in modified form, are summarized in Table 1.

The US Army is a leader in sustainable design and development. The army created the Sustainable Project Rating Tool (SPiRiT), derived from LEED version 2.0. Since 2006, SPiRiT has been required for all army construction and residential projects. Every Army employee is a member of the USGBC. SPiRiT includes extra points, not included in LEED. Extra points, particular to SPiRiT, that can be applied to bridge construction, either directly or in modified form, are summarized in Table 1.

Life Cycle Thinking

Life cycle thinking is integral to green design. This approach involves considering all stages of a bridge's life: raw material acquisition, transportation, fabrication, use, maintenance, and salvage/disposal. The EPA refers to this as a "cradle-to-grave" approach. William McDonough, a prominent architect and green design leader, dismisses cradle-to-grave terminology and advocates a "cradle-to-cradle" approach. Cradle-to-cradle terminology puts an emphasis on designing for re-use, recycling, or composting and highlights the undesirability of landfills as "grave". The US Army has adopted cradle-to-cradle terminology.

Adopting life cycle thinking is perhaps the single most effective measure bridge engineers can take towards achieving green designs. Life cycle thinking is applied in two distinct regimes, Life Cycle Cost Analysis and Life Cycle Assessment, both of which are discussed below.

LIFE CYCLE COST ANALYSIS

Life cycle cost analysis is used to evaluate alternative designs based on lowest total cost, instead of merely lowest construction cost. This total life cycle cost includes agency, user, and vulnerability costs. Agency costs include design, construction, maintenance, rehabilitation, and salvage/disposal. User costs include detours, lost travel time, and accidents. Vulnerability costs are those associated with potential bridge failure due to earthquake, scour, storm, flooding, collision, overload, fatigue, or other risks. Vulnerability costs are factored according to the probability of occurrence.

On August 10, 2005, the President signed into law the $244.1 billion Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users. Section 1904 of this law requires an independent value engineering review on bridge projects with an estimated total cost of $20 million or more. For bridge projects, value engineering is defined to include an analysis of life cycle costs. The NCHRP Report 483 "Bridge Life Cycle Cost Analysis", published in 2003, provides comprehensive methodology and is accompanied by free BridgeLCC software.

The famed bridge engineer J.A.L. Waddell, in his 1923 book “Bridge Economics”, recommended an early form of life cycle cost analysis with detailed estimating of bridge costs related to construction, maintenance, and interest. While Mr. Waddell neglected the user and vulnerability costs included in modern analyses, he did recognize the need of considering costs other than first construction.

Table 1- LEED Green Design Strategies Applicable to Bridges

Based on LEED-NC Version 2.2 (2007)

Sustainable Sites

SS.P1 - Prevent soil erosion and dust pollution from the construction site.
SS.C1 - Do not develop land that is prime farmlands, wetlands, endangered species habitat or parkland.
SS.C2 - Construct on previously developed land. Encourage community connectivity and density.
SS.C3 - Construct on brownfield sites. Rehabilitate the existing environmental contamination.
SS.C4.1 - Encourage public transportation by providing a commuter rail line or bus lane.
SS.C4.2 - Encourage bicycle use by providing a bike lane.
SS.C4.3 - Encourage car pools and low-emitting vehicles by providing a designated lane.
SS.C5.1 - Conserve existing natural areas and restore damaged areas to provide habitat and biodiversity.
SS.C5.2 - Provide a high ratio of open space to development footprint to promote biodiversity.
SS.C6.1 - Reduce storm water runoff by reducing impervious cover.
SS.C6.2 - Reduce or eliminate pollution from stormwater runoff.
SS.C7 - Reduce heat island effects by providing shade trees or low reflectance surfaces.
SS.C8 - Minimize light pollution.

Water Efficiency

WE.C1 - Eliminate the use of potable water for landscape irrigation. Favor indigenous plants.

Energy and Atmosphere

EA.P1 - Commission the energy related systems to verify performance conforms with the design.
EA.P2 - Establish the minimum level of energy efficiency.
EA.C1 - Optimize energy performance.
EA.C2 - Provide on-site renewable energy systems.
EA.C5 - Provide for the ongoing accountability of energy consumption over time.
EA.C6 - Use grid-source green electricity utilizing a renewable energy source.

Materials and Resources

MR.C1 - Reuse portions of on-sight existing structures.
MR.C2 - Divert construction debris from disposal in landfills and incinerators; redirect to recycling or reuse.
MR.C3 - Reuse building materials and products.
MR.C4 - Utilize recycled content materials.
MR.C5 - Utilize regionally (<500 miles) extracted, processed and manufactured materials.
MR.C6 - Utilize rapidly renewable materials.
MR.C7 - Utilize FSC certified wood.

Indoor Environmental Quality

EQ.P1 - Ensure proper ventilation for maintenance access areas.
EQ.C6 - Provide controllable lighting for maintenance access areas.
EQ.C8 - Provide daylighting for maintenance access areas.

Innovation and Design Process

ID.C1 - Innovate design beyond the available LEED credits.
ID.C2 - Include one or more LEED Accredited Professionals on the project team.

US Army SPiRiT

6.C1 - Holistic delivery process including charettes, life cycle costing, identification of goals and metrics.
7.C1 - Develop a facility operations and maintenance program.
7.C1 - Provide surfaces and equipment that are appropriately durable, according to life cycle cost analysis.
7.C2 - Provide a healthy safe work environment for maintenance staff to promote quality of life and productivity.
8.C1 - Assess the functional life of the facility considering economic, functional, and physical obsolescence.
8.C2 - Identify future uses for the facility and design to accommodate foreseeable change.

Bridge engineers have been slow to adopt life cycle cost analysis, often designing for lowest construction costs. Unlike the metric system and load resistance factor design, which bridge engineers have also been slow to adopt despite federal regulation, life cycle cost analysis has the potential to lead towards more sustainable designs. It costs money to damage the environment. Decreasing total life cycle costs will tend to decrease environmental damage.

LIFE CYCLE ASSESSMENT

Life cycle assessment is the tool that is used to estimate carbon dioxide emissions, or the "carbon footprint", of a product or service. The assessments are used to estimate many other types of environmental impacts, including energy and material resource inputs, as well as waste and pollution outputs. See Figure 1. There are two distinct approaches to performing a life cycle assessment: process based and economic input-output based.

Process Based

Process based life cycle assessments have been standardized by the International Standards Organization and the US Environmental Protection Agency. This method makes a detailed tally of environmental impacts. A process based assessment for a steel bridge would begin tallying at the iron ore mine, add transportation to the steel mill, and continue tallying impacts at every step of bridge life until it is demolished and salvaged. For the construction phase, each of the contractor's cranes, generators, trucks and tugs would be added to the tally. The final tally would include each ton of carbon dioxide, BTU of energy, and any other input or output of interest. This type of assessment can take months or years to perform.

The trouble with the process based approach, beyond the extra-ordinary amount of time required to perform the assessment, is that bridge designers cannot predict or control the particulars. Bridge designers don't know if the iron will come from taconite ore of Minnesota or magnetite ore of Michigan. Maybe the steel will come from a mini-mill which uses mostly scrap steel, instead of iron ore. The environmental impacts for a given bridge design will vary depending on countless unknowns.

Economic Input Ouput

Carnegie Mellon Green Design Institute has developed an economic input-output approach to life cycle assessment with associated free internet based software (www.eiolca.net). Bridge designers can use the method to compare the environmental impacts of alternatives during type study and preliminary design phases of a project. This assessment "takes a more aggregate view of the sectors producing all of the goods and services in the US economy” (Hendrickson 2006) and can be performed in a matter of hours.

This method makes use of economic input-output tables prepared by the US Department of Commerce. The US economy is divided into 491 sectors based on the North American Industry Classification System. Sectors of interest to bridge professionals are listed in Appendix D.

The interrelationship and supply chain of each sector is modeled. Wassily Leontief won the Nobel prize in economics for conceiving of the tables. All developed countries, except Iceland, publish input-output tables for their economy. Mr. Leontief was also the first to recognize, in 1970, that the model could be used to estimate environmental impacts.

The eiolca.net software uses an input of 1997 US dollars to determine the outputs in terms of global warming potential, conventional air pollution, toxic releases, energy releases, as well as employment, and economic activity.

Several cost indexes are available to adjust for inflation between current dollars, and the 1997 dollars required to perform the assessment (See Appendix B). Per data collected by the Washington State Department of Transportation, the construction costs for steel and reinforced concrete highway structures in 2008 are, respectively, 2.2 and 1.9 times higher than the 1997 costs. The consumer price index, as tracked by the Bureau of Labor Statistics, has risen 1.33 times since 1997.

Hybrid

It is possible to combine the process based and economic input-output approaches to create a hybrid life cycle assessment. See the literature review in Appendix A for a summary of the dissertation by Aurora Sharrad. The hybrid model created by Ms. Sharrad (www.eiolca.net/aurora-hybrid.html) is well suited to green bridge design.

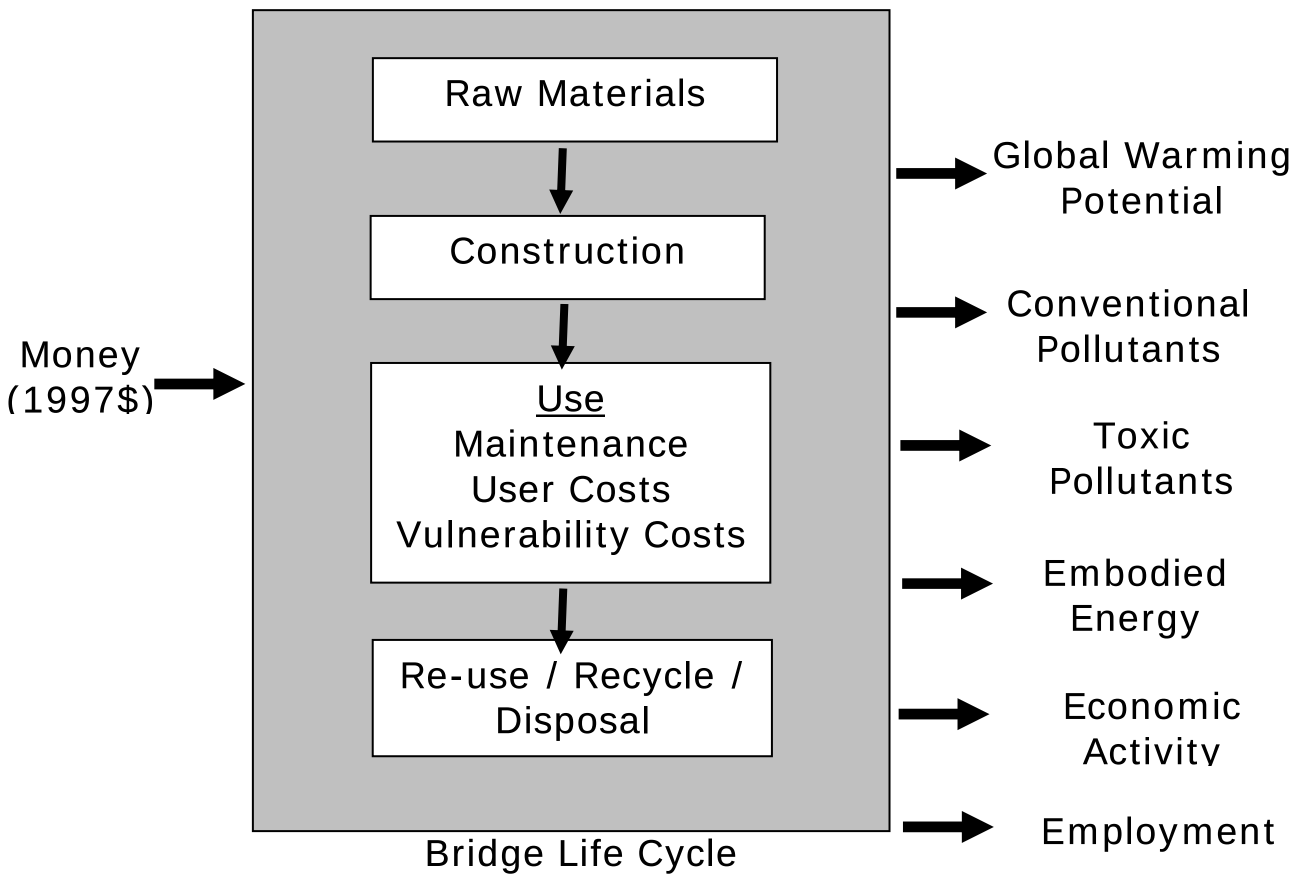

Figure 1 – Schematic of Bridge Life Cycle Assessment using

www.eiolca.net

Discussion of Steel versus Concrete versus Movable Bridges

Which bridge design will have a smaller environmental impact: a high level concrete fixed bridge, a high level steel fixed bridge or a low level movable bridge? This question can be answered for a given site with competing bridge designs by performing life cycle cost analyses and life cycle assessments for each alternative.

Raw Materials and Construction

The global warming potential for relevant commodities, in terms of metric tons of carbon dioxide equivalent, are listed below for each million 2008 dollars purchased. These values are the average across the US economy, are based on www.eiolca.net and are corrected for inflation.

Ready-mix concrete	: 1100	Engineering services	: 110
Rolled steel	: 650	Truck transporation	: 1590
Steel forging	: 490	Water transportation	: 1080
Steel casting	: 420	Rail transportation	: 850
Steel casting	: 420	Air transportation	: 1360
Bridge construction	: 480	Power generation	: 7910
Bridge maintenance	: 520		

Alterations to the material specifications such as using recycled materials, or using industrial by-products in concrete mix design will reduce carbon emissions. The Sunshine Skyway Bridge in Florida and the Oakland Bay Bridge in California both used concrete mixes with fly ash content of 50% replacement for Portland cement. Pozzolans such as fly ash, silica fume, and blast furnace slag have no carbon emissions associated with manufacture, since they are industrial by-products. Unlike Portland cement, pozzolans have no carbon emissions associated with calcination.

Use

Yanev (2007) reports that the maintenance costs for steel bridges, including painting, are approximately 1% of the bridge replacement cost per year. Steel bridges fabricated from un-painted weathering steel and concrete bridges, with no painting required, cost approximately 0.5% to maintain. A reasonable assumption for the operation and maintenance of steel movable bridges is 1.5 to 2%.

User costs are associated with traffic delays caused by movable bridge span openings. High level bridges in urban areas will tend to have user costs and business effects associated with the nuisance of the approach spans. BridgeLCC does not typically account for user costs associated with increased fuel use due to the roadway elevation changes of high level fixed bridges.

Low level movable spans are more likely to be subject to the vulnerability costs associated with flooding.

Re-use / Recycle / Disposal

Steel has an approximate salvage value of 25 cents per pound. “Nearly 100% of the beams and plates used in construction are recycled into new steel products at the end of their useful life”, per the Steel Recycling Institute. Concrete has no salvage value. A recent study by the FHWA indicates that the majority of states allow concrete to be crushed and recycled as a lower grade of aggregate.

Life-Cycle

Concrete and steel are both used for the structures of green buildings. Both materials are viable for constructing green bridges.

Conclusions and Recommendations

There is no existing standard for the green design of bridges or transportation infrastructure. It is inevitable that this void will soon be filled by AASHTO, USGBC, or another entity. Bridge professionals need not wait and can apply the following established green building strategies:

Design according to applicable LEED credits. See Table 1.

Select design alternatives by performing bridge life cycle analysis, as required by federal legislation. Do not select alternatives based on lowest construction cost only. The free BridgeLCC software is recommended.

Perform life cycle assessment to determine global warming and pollution emissions associated with each alternative bridge design. The free software available at www.eiolca.net is recommended.

Appendix A – Literature Review

This section summarizes various documents relevant to green design for bridges.

"Climate Change 2007: Synthesis Report, Fourth Assessment Report", by Intergovernmental Panel on Climate Change: "There is high confidence [80%] that neither adaptation nor mitigation alone can avoid all climate change impacts; however, they can complement each other and together can significantly reduce the risks of climate change (page 20)."

"Potential Impacts of Climate Change on US Transportation, Special Report 290", by Transportaion Research Board, 2008: "Every mode of transportation will be affected as climate change poses new and often unfamiliar challenges to infrastructure providers (page 14)." "The US transportation system was built for the typical weather and climate experienced locally, including a reasonable range of extremes. If projected climate changes push environmental conditions outside the range for which the system was designed – and the scientific evidence suggests this will be the case – the impacts will be significant (page 56)." "Thus there is a need for…making changes in [design] standards that focuses first on long-lived facilities, such as bridges (page 11)."

"Environmental Repercussions and Economic Structure: An Input-Output Approach", by Wassily Leontief, 1970: "Within the framework of the open input-output system...any reduction or increase in the output level of pollutants can be traced to changes in the final demand for specific goods and services, changes in the technical structure of one or more sectors of the economy, or to some combination of the two (page 4)." "Pollutants can be analyzed as what they actually are – integral parts of the economic process (page 8)."

"Environmental Life Cycle Assessment of Goods and Services, An Input-Output Approach", by Chris T. Hendrickson, et al., 2006: This book was written by a group of researchers from Carnegie Mellon's Green Design Institute as a companion to their free on-line software for economic input-output life cycle assessment: www.eiolca.net

"Steel versus Steel-Reinforced Concrete Bridges : Environmental Assessment", by Arpad Horvath and Chris Hendrickson, 1998: This paper uses the www.eiolca.net method to compare the life cycle environmental impacts of steel and concrete bridge designs. A single case study is used, based on competing bids for the US 231 Bridge over the White River in Indiana. For the given case study, the concrete girder design was preferred over steel girders in terms of construction cost, life cycle cost, and environmental impact.

"Greening Construction Processes Using and Input-Output-Based Hybrid Life Cycle Asessment Model", by Aurora L. Sharrard, 2007: This doctoral dissertation "focuses on the efficiency, economic effect, and environmental impact of construction activities, *not* construction materials (page 3)." "It is the eventual goal of this research to encourage construction companies to use the hybrid life cycle analysis tool [www.eiolca.net/aurora-hybrid.html] to target potential areas of improvement on their own (page 5)." The environmental impacts of various construction projects are calculated, including a bridge superstructure repair on the Pennsylvania Turnpike.

"Lifecycle Analysis of Bridges Considering Longevity of Bridge and Severe Earthquakes", by Y. Itoh, et al., 2003: The life cycle costs and carbon emissions for steel bridges of various designs and span lengths are presented. Rationalized structural details are suggested.

"Environmental Benefits of Life Cycle Design of Concrete Bridges", by Z. Lounis and L. Daigle, 2007: "High performance concrete with low permeability and high strength can be obtained using: (i) low water-to-cement ratios; or (ii) by adding reclaimed industry byproducts such as fly ash (byproduct of coal combustion for electric power generation), granulated blast-furnace slag (byproduct of steel manufacturing), and silica fume (byproduct of semi-conductor manufacturing as supplementary cementing materials (page 3)." "The use of high performance concrete materials results in bridge decks with extended service lives, reduced life cycle costs [for both agency and user costs] and better environmental profiles when compared to conventional normal concrete bride decks (page 6)."

"Aspects of Concrete bridges in Sustainable Development", by A.J. Martin, 2003: A case study of the environmental impacts of three designs for the Second Stichtse Bridge in the Netherlands is presented. The three evaluated designs are for box girders fabricated from lightweight concrete, normal density concrete, and high strength concrete. The high strength concrete design was found to have a slight (three percent) advantage in terms of embodied energy.

"How Sustainable is Concrete?", by Leslie Struble and Jonathan Godfrey, 2004: This paper uses a process based life cycle assessment to compare the environmental impacts of fabricating a simply supported concrete beam to a steel I-beam of the same moment capacity. The concrete beam has a rectangular section with tensile reinforcing steel only. The concrete strength is 4350 psi with 10% of the Portland cement replaced with fly ash. The steel rebar has 60 ksi yield strength. The steel for the beam has 36 ksi yield strength and is assumed to contain an average amount of scrap steel. The results indicate that less carbon dioxide is emitted (%11) in fabricating the steel beam, but more energy (64%) is used, when compared to fabricating the concrete beam.

"Recycled Roadways", by Jason Harrington, 2005: This article, appearing in Public Roads magazine, discusses the Federal Highway Administration's recycled materials policy and the work of their Recycling Team. "Recycling of aggregates and other highway construction materials makes sound economic, environmental, and engineering sense." Successful state programs for using recycled asphalt, concrete, industrial byproducts, and scrap tires are presented.

"Recycling and Use of Waste Materials and By-Products in Highway Construction, Synthesis of Highway Practice 199", by Robert J. Collins and Stanley K. Ciesielski, 1994: "This synthesis [published by the Transportation Research Board] discusses the recycling and use of various waste materials and byproducts in highway construction and maintenance operations. Waste materials and byproducts are classified into four broad categories based on their source: agricultural, domestic, industrial, and mineral. More than 30 different sources of waste materials and by products were surveyed. The quantities, characteristics, possible uses, current and past research activities, and actual highway construction use of each waste material or byproduct is discussed."

"Synthetic Lightweight Aggregate for Highway Construction", by Moshen G. Kashi, et al., 2001: "This research has shown that synthetic aggregates can be developed from compounding coal fly ash and recycled high-density polyethylene, HDPE (page 1)." Only 10% of coal fly ash is suitable for use as a Pozzolan admixture. Rejected fly ash can be combined with post consumer plastics from the municipal waste stream to produce synthetic lightweight aggregate. The resulting concrete meets the weight (1900 kg/m^3 maximum) and strength (2500 psi minimum) requirements of ACI 213R-87 for lightweight concrete. "Future research efforts should be concentrated on the experimental use of synthetic lightweight concrete for...bridge decks (page 58)."

"Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the US Cement Industry", by Nathan Martin, et al., 1999: "This paper reports on an in-depth analysis of the U.S. cement industry, identifying cost-effective energy efficiency measures and potentials (page 1)." "We examined 30 energy efficient technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of the measures (page 1)." Cost effective measures, defined as having a payback period of 3 years or less, could reduce energy use by 18% and carbon emissions by 16%. The majority of the carbon emissions reduction potential is attributed to the increased usage of blended cement. "The use of blended cements is a particularly attractive efficiency option since…[it] not only allows for a reduction in the energy used (and carbon emissions) in clinker production, but also corresponds to a reduction in carbon dioxide emissions in calcination as well. (page 27)."

"Energy Efficiency and CarbonDioxide Emissions Reduction Opportunities in the U.S. Iron and Steel Sector", by Ernst Worrell, et al., 1999: "This paper presents an in-depth analysis of the U.S. iron and steel industry, identifying cost-effective energy and carbon dioxide emissions savings that can be achieved both today and in the near future (page 1)." "Compared to other large steel producers, the US still tends to have higher energy intensities and has a large technical potential to achieve best practice levels of energy use for steel production (page 1)." Cost effective equivalent measures have "an achievable energy savings of 18% of 1994 U.S. iron and steel energy use and a roughly equivalent savings (19%) of 1994 U.S. iron and steel carbon dioxide emissions (page 1)."

"Bridge Management", by Bojidar Yanev, 2007: "Empirical evidence therefore suggests that annual maintenance level amounting to 1% of the replacement cost is a threshold below which deterioration accelerates (Section 11.4, page 384)." "Researchers investigated comparable practices worldwide and recommended a full (100%) maintenance consisting of 15 tasks (page 384)." The recommended tasks are debris removal, sweeping, cleaning drains, cleaning piers, gleaning grating, cleaning joints, washing deck, painting, spot painting, sidewalk curb repair, pavement sealing, electric maintenance, mechanical maintenance, wearing surface, and washing the underside. The cost, in 2007 dollars per square meter of deck, and recommended frequency of each task is presented in Table E23.1. "[Painting and spot painting] amount to 66% of the recommended annual maintenance cost (page 392)."

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