Sustainable High Performance Concrete Buildings

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SUSTAINABLE BUILDINGS

Sustainable buildings are achieved through integrated building design—an approach to design and construction that involves the participation of owners, contractors, suppliers, building users, and design professionals during the initial design phase and at other key points in the design process. The goal of integrated design is to achieve high performance and synergistic benefits that minimize a building's environmental impacts throughout its life cycle. For example, in an integrated design approach, the mechanical engineer will calculate energy use and cost very early in the design process, and inform designers of the energy-use implications of building orientation, configuration, fenestration, mechanical systems, and lighting options. Similarly, the participation of structural engineers in the integrated design process can create opportunities for green design strategies. For example, the choice of structural system, whether steel, wood, or concrete, during the initial design phase can affect the amount of energy needed for heating and cooling, as well as the ability to incorporate local and recycled-content materials into the building project.

This paper describes the aspects of concrete construction that contribute to sustainable buildings. The discussion will refer to the point system of the *Leadership in Energy and Environmental Design Green Building Rating System for New Construction and Major Renovation (LEED-NC)* [USGBC, 2005]. *LEED-NC* is a voluntary rating system for designing, building, and certifying green buildings. It is widely used to determine if a new building meets the behavior requirements for the level of LEED rating required by the owner. Sustainable aspects of green buildings are often grouped into categories so that members of the design team have a structure around which to integrate green design strategies into a sustainable design. LEED-NC uses the following five categories:

- Sustainable site planning and use
- Safeguarding water and water conservation
- Energy conservation and protection of the atmosphere
- Efficient use of materials and resource conservation
- Protection of indoor environmental quality

ENERGY AND ATMOSPHERE, OPTIMIZE ENERGY PERFORMANCE

A recent research project using whole-building energy simulation showed that the effect of thermal mass in concrete framed buildings, combined with thermal improvements to the building envelopes, lowers energy cost up to 23% relative to a baseline steel framed building with EIFS (exterior insulation finishing system) [Marceau and VanGeem, 2007a]. This energy savings qualifies for up to four points (Energy and Atmosphere Credit 1: Optimize Energy Performance). As of June 2007, all LEED projects are required to achieve at least two points under Optimize Energy Performance. The results of the research project provide in-depth information on potential energy savings in mid-rise commercial buildings.

Several buildings were modeled in a range of climates to demonstrate how the thermal properties of concrete in buildings can result in energy cost savings beyond *ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2004). Two structural systems were considered, structural steel and precast concrete frame, along with four different cladding, EIFS, curtain wall, precast walls meeting energy code requirements, and precast concrete walls exceeding energy code requirements. The modeling conforms to the requirements of Informative Appendix G: Performance Rating Method in *ASHRAE 90.1*. Points in *LEED-NC* “Energy and Atmosphere Credit 1: Optimize Energy Performance” are awarded if energy cost savings can be shown compared to a *baseline* building, which is one that meets the requirements in Appendix G. When concrete is considered, it is necessary to use a whole-building energy simulation program that can calculate yearly energy use at hourly intervals. Such detailed temporal resolution is needed to realistically simulate the beneficial thermal mass effects of concrete. The number of points awarded will depend on the building, the climate in which it is located, fuel costs, and the minimum requirements of the standard. In *LEED-NC*, from 1 to 10 points are awarded for energy cost savings of 15% to 60% for new buildings and 5% to 50% for existing buildings.

All buildings in the study are five-story commercial buildings with plan dimensions 105 by 105 ft (32 by 32 m). The baseline building consists of an exterior insulation finishing system (EIFS) with steel stud walls, structural steel frame, and metal deck floors with concrete topping slab. In addition to the baseline buildings, there are nine proposed buildings. All are variations of the structure and building envelope of the baseline building. Table 1 provides a summary of the differences between the baseline building and the proposed buildings. The proposed buildings were chosen to explore the effect of different amounts of concrete on energy use in a variety of scenarios. In addition, the curtain wall building was chosen because it is a common building type. In this paper, a curtain wall is a façade that does not carry any dead load from the building other than its own dead load and consists of an aluminum frame in-filled with a combination of glass and insulated metal pans. Further, for a given climate the curtain wall and EIFS have the same U-factor, but the curtain wall has less thermal mass. The modeled scenarios are:

- EIFS and curtain walls meeting *ASHRAE 90.1-2004* with either structural steel or reinforced concrete frame (EL, CL, EM, CM),
- Precast concrete walls meeting *ASHRAE 90.1-2004* with either structural steel or reinforced concrete frame (ML, MM),
- Precast concrete walls exceeding *ASHRAE 90.1-2004* with either structural steel or reinforced concrete frame (MLX, MMX),
- Precast concrete walls meeting *ASHRAE 90.1-2004*, reinforced concrete frame, and high internal load equipment placed near the central core of the building (MMI), and

- Precast concrete walls exceeding *ASHRAE 90.1-2004*, reinforced concrete frame, and high internal load equipment placed near the central core of the building (MMXI).

Designation*	Exterior walls	Structural frame	Floors	Interior walls
EL (baseline)	EIFS & metal stud	structural steel	concrete on metal deck	metal stud
CL	curtain wall	structural steel	concrete on metal deck	metal stud
ML	precast concrete	structural steel	concrete on metal deck	metal stud
EM	EIFS & metal stud	reinforced concrete	12" (300 mm) solid concrete	reinforced concrete
CM	curtain wall	reinforced concrete	12" (300 mm) solid concrete	reinforced concrete
MM	precast concrete	reinforced concrete	12" (300 mm) solid concrete	reinforced concrete
MLX	precast concrete exceeding code	structural steel	concrete on metal deck	metal stud
MMX	precast concrete exceeding code	reinforced concrete	12" (300 mm) solid concrete	reinforced concrete
MMI**	precast concrete	reinforced concrete	12" (300 mm) solid concrete	reinforced concrete
MMXI**	precast concrete exceeding code	reinforced concrete	12" (300 mm) solid concrete	reinforced concrete

*See text for an explanation of the designations.
**High internal load equipment placed near the central core of the building.

TABLE 1 - BUILDINGS MODELED

The first letter of the abbreviated building designation refers to the exterior wall system: “E” for EIFS, “C” for curtain wall, or “M” for precast concrete (the letter M is used because of the thermal mass effects of concrete). The second letter refers to the structural framing system and interior walls and floors: “L” for light and “M” for mass. The light materials are structural steel framing and metal deck floors with concrete topping slab. The mass materials are reinforced concrete framing and 12-in. (300-mm) concrete floors. Although a common thickness for post-tensioned concrete floors is 8 in. (200 mm), a 12-in. (300-mm) thick floor is investigated in this study because this thickness allows for longer spans and more usable floor space. Other floor thicknesses were modeled to determine their sensitivity to the results. The results show that floor thicknesses between 7.5 and 12 in. (190 and 300 mm) result in very similar energy use. An “X” indicates that the building envelope exceeds *ASHRAE 90.1-2004* requirements and an “I” indicates that the internal loads are clustered near the central core of the building.

Buildings EM, CM, and MM are similar to EL, CL, and ML, respectively, except they have more concrete in interior floors and walls. Buildings MLX and MMX are similar to ML and MM, respectively, except their building envelopes modestly exceed code. Buildings MMI and MMXI are similar to MM and MMX, respectively, except that internal loads are assumed to be clustered near the central core of the building, where most of the interior concrete is located.

Energy Cost Savings

The results are of the energy analysis are presented in Figure 1. In four of the six cities where buildings were modeled, reinforced concrete frame buildings with concrete walls and building envelopes that exceed code will most likely qualify for points under Energy and Atmosphere Credit 1. In the cold climate category (Denver and Chicago), these buildings will likely qualify for 3 points, that is, at least 17.5% energy cost savings. In the cool climate category (Salem), these buildings will likely qualify for 4 points, that is, at least 21% energy cost savings. In the mild climate category (Memphis), these buildings will likely qualify for 2 points, that is, at least 14% energy cost savings. In addition, the steel frame buildings with concrete walls and windows exceeding code will likely qualify for 2 points, at least 14.5% energy savings, in Salem and Denver.

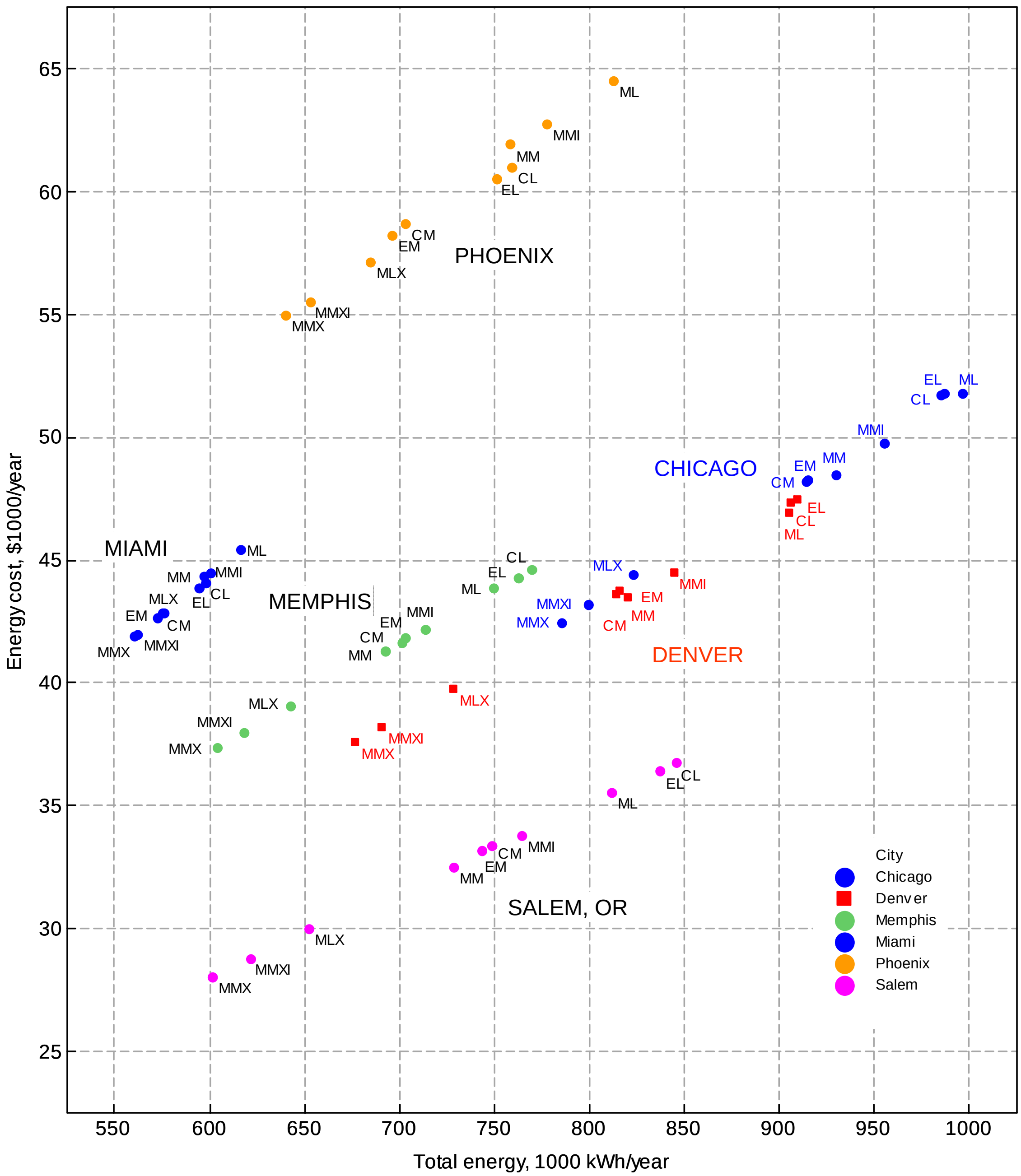

FIGURE 1 - THE RELATIONSHIP BETWEEN ANNUAL ENERGY USE AND COST VARIES BY CITY. SEE TABLE 1 FOR AN EXPLANATION OF THE BUILDING DESIGNATION ABBREVIATION

Due to thermal mass effects, *AHSRAE 90.1-2004* does not require mass walls to have as high an R-value as low-mass walls. Comparing buildings with the same structural frame but different walls shows small differences in energy cost savings. These results indicate that the reduced R-values for mass walls allowed in energy codes are justified. For a given structural frame, the EIFS and curtain wall buildings in Miami and Phoenix use comparable energy to the buildings with uninsulated mass walls. In Miami they use about 3% less energy, and in Phoenix they use about 6% less energy.

In Memphis, Salem, Denver, and Chicago, energy cost savings of 6 to 9% are indicated for the three concrete frame buildings meeting code compared to the three steel frame buildings meeting code. This energy cost savings is primarily due to the concrete shear walls in the concrete frame building. The exterior wall construction is identical in each pair of comparisons.

FROM THE GROUND UP: SUSTAINABLE SITES, BROWNFIELD REDEVELOPMENT

Infill development on vacated sites is a green design strategy that reduces the need for new infrastructure, such as roads and sewers. However, these sites are sometimes contaminated with hazardous materials from the activities of previous tenants. For example, dry cleaning and gas stations have been known to produce high levels of subsurface contamination. Such sites are called *brownfields*. In order to make brownfield sites suitable for development, the contaminated soil must either be treated (on-site or off-site) or excavated and disposed of in a landfill. On-site treatment through cement solidification and stabilization is often preferable because it avoids the energy and emissions associated with excavation and transportation, eliminates the potential exposure to contaminated material, and conserves landfill space. The treatment involves mixing portland cement and water into the contaminated material with an auger to encapsulate contaminants and reduce leaching concentrations to below regulatory levels. By immobilizing hazardous material within the contaminated material, solidification and stabilization prevents exposure to contaminants. Treatment through on-site stabilization and solidification has positive consequences for foundation design because it increases the bearing capacity of soil [Freeman and Harris, 1995]. In *LEED-NC*, this strategy is worth one point (Sustainable Sites Credit 3: Brownfield Redevelopment).

MATERIALS AND RESOURCES, RECYCLED CONTENT

The requirements of “Materials and Resources Credit 4.1 and 4.2: Recycle Content” are for using materials with recycled content. One point is awarded if the sum of the post-consumer recycled content plus one-half of the pre-consumer recycled content constitutes at least 10% of the total value of the materials in the project. The value of the recycled content of a material is the weight of the recycled content in the item divided by the weight of all materials in that item, and then multiplied by the total cost of the item. Supplementary cementitious materials, such as fly ash, silica fume, and slag cement are considered pre-consumer. Fly ash is a by-product of generating electricity from coal and slag cement is produced from molten blast furnace slag. In contrast, using recycled concrete as aggregate instead of extracted (virgin) aggregates would qualify as post-consumer. Although reinforcing bars are manufactured from recycled steel, in *LEED-NC*, reinforcing is not considered part of concrete (reinforcing material should be considered as a separate item). This credit is worth 1 point for the quantities quoted above and 2 points if the quantities are doubled to 20% combined post-consumer plus one-half pre-consumer recycled content.

Reducing environmental impacts can also be achieved by specifying later age strengths for concrete, such as 28-days instead of 7-days. Unless there is a specific need, avoiding specifying high early strengths can keep the amount of portland cement in a concrete mix to a minimum. Although portland cement is only 7 to 15% by mass in ordinary portland cement concrete, it represents 85 to 90% of the embodied energy [Marceau, Nisbet and VanGeem, 2007]. Another way to minimize environmental impacts is to replace cement with fly ash or slag cement. Fly ash is commonly used at cement replacement levels up to 25% and slag cement up to 60%. When these supplementary cementitious materials are used, the proportioned mixture (using actual project materials) should be tested to determine that it meets the specified concrete properties for the project. Strength development is generally slower so construction schedules must accommodate the extra time required before forms and shoring are removed. Special precautions may also be needed in cold weather to ensure adequate strength development.

Structural engineers are reluctant to use recycled aggregate from crushed concrete in structural concrete. In northern climates recycled concrete from pavement may be contaminated with road salts, which is undesirable because it may promote corrosion in steel reinforced concrete. However, recycled concrete is frequently used as clean fill around foundations or base for pavements.

MATERIALS AND RESOURCES, REGIONAL MATERIALS

"Materials and Resources Credits 5.1 and 5.2: Regional Materials" support the use of local building materials and products that are extracted and manufactured within the region, thereby supporting the use of indigenous resources and reducing the environmental impacts resulting from transportation. The requirements of this credit state: "Use building materials or products that have been extracted, harvested, or recovered, as well as manufactured, within 800 km (500 miles) of the project site for a minimum of 10% (Credit 5.1) or 20% (Credit 5.2) based on cost of the total materials value." Concrete will likely qualify since all material in ordinary portland cement concrete is usually extracted and manufactured locally. Cement plants are within 500 miles of most large cities, aggregate is closer still. Materials are assembled on-site or at ready mix plants within 80 km (50 miles) of most building sites. Fly ash and slag cement are transported an average of 150 km (95 miles). Credit 5.1 is worth 1 point, and Credit 5.2 is worth an additional 1 point.

SUSTAINABLE SITES, HEAT ISLAND EFFECT

Structural systems that are designed to support a roof with concrete ballast pavers contribute to lowering energy use for air conditioning, reducing the urban heat island effect, and reducing the associated smog because concrete, which is light colored, is reflective in the solar spectrum (reflects heat from the sun). Concretes generally have a solar reflectance of at least 0.3, corresponding to a solar reflectance index (SRI) of 29. Concrete can be made very reflective (solar reflectance of at least 0.64 and SRI of 78) with slag cement or white portland cement [Marceau and VanGeem, 2007b]. One point can be earned for using low-sloping roofing with an SRI of at least 78 or steep-sloped roofing with an SRI of at least 29 for a minimum of 75% of the roof surface (Sustainable Sites Credit 7.2: Heat Island Effect, Roof).

OTHER POINTS

Concrete has many other sustainable attributes that are not directly related to structural considerations.

Concrete parking garages within buildings can be used to limit site disturbance, including earthwork and clearing vegetation. Parking garages within buildings help maintain existing natural areas that would otherwise be consumed by paved parking. This strategy is worth one point (Sustainable Sites Credit 5.1: Site Development, Protect or Restore Habitat). Parking garages on the lower floors of a building can also be used to help reduce the footprint of the development. This is worth one additional point (Sustainable Sites Credit 5.2: Site Development: Maximize Open Space).

Using pervious concrete pavements will reduce the rate and quantity of storm water runoff because they increase infiltration of stormwater. Pervious concrete contains coarse aggregate, little or no fine aggregate, and insufficient cement paste to fill the voids between the coarse aggregate. It results in concrete with a high volume of voids (15% to 30%) and a high permeability that allows water to flow through easily. Similar results can be achieved by using concrete grid pavers that have large voids where vegetation can grow. Using pervious concrete pavements or grid pavers can help earn one point (Sustainable Sites Credit 6.1: Stormwater Design: Quantity Control).

Concrete structures are resistant to fires, wind, hurricanes, floods, earthquakes, wind-driven rain, and moisture damage. Since concrete in buildings is durable and has a long life, the core and shell of a concrete building can be reused when undertaking in major renovation. This strategy is worth 1 to 2 points: 1 point if 75% of the existing building structure/shell is left in place and 2 points if 95% is left in place (Materials and Resources Credit 1: Building Reuse).

If a concrete structure is demolished, it is frequently crushed and recycled into aggregate for road bases or construction fill. This diverts material from landfill disposal. This strategy is worth 1 point if 50% of construction, demolition, and land clearing waste on a construction project is recycled or salvaged and 2 points for 75% (Materials and Resources Credit 2: Construction Waste Management).

Concrete has low emissions of volatile organic compounds and does not degrade indoor air quality. If properly coated, the concrete structure itself, such as floors, walls and ceilings, can be the finished surface, eliminating the need for additional sheathing materials. This strategy could be worth one point (Innovation and Design Process).

CLIMATE CHANGE

In an era of increased attention on climate change, concrete performs well when compared to other building materials. As with any building product, concrete and its ingredients do require energy to produce that in turn results in the generation of carbon dioxide or CO_2. But the amount of CO_2 produced during manufacturing and the net impact of using concrete as a building material is relatively small. Concrete is resource efficient and the ingredients require little processing. Water, sand, stone or gravel and other ingredients make up about 90% of the concrete mixture by weight. The process of mining sand and gravel, crushing stone, combining the materials in a concrete plant and transporting concrete to the construction site requires very little energy and therefore only emits a relatively small amount of CO_2 into the atmosphere. Most materials for concrete are harvested and manufactured locally which minimizes transportation energy.

Concrete uses about 7 to 15% cement by weight depending on the performance requirements for the concrete. The average quantity of cement is around 250 kg/m^3 (420 lb/yd^3). One cubic meter (m^3) of concrete weighs approximately 2400 kg (1 cubic yard weighs approximately 3800 lbs). As a result of using cement in concrete, approximately 100 to 300 kg of CO_2 is embodied for every cubic meter of concrete (170 to 500 lb per yd^3) produced or approximately 5% to 13% of the weight of concrete produced. The quantity is directly related to the quantity of portland cement used.[3] A significant portion of the CO_2 produced during manufacturing of cement is reabsorbed into concrete during the product life cycle by a process called carbonation. One research study estimates that between 33% and 57% of the CO_2 emitted from calcination will be reabsorbed through carbonation of concrete surfaces over a 100 year life cycle.[8]

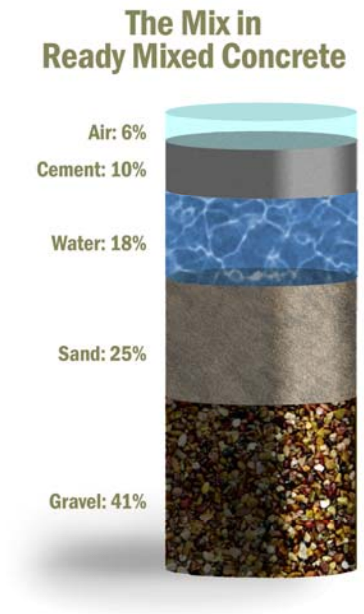

FIGURE 2 - TYPICAL COMPOSITION OF HYDRAULIC CEMENT CONCRETE

One research study compared the energy of production for concrete and other common building materials for raw material extraction, transportation, and manufacturing. Figure 3 provides a summary of a study which concluded that the energy required to produce one metric ton of reinforced concrete was 2.5 GJ/t compared to 30 GJ/t for steel.[9] The same study compared the CO_2 emissions of several different building materials per metric ton (1000 kg) for residential construction and concluded that concrete produced 147 kg of CO_2, metals produced 3000 kg of CO_2, and wood produced 127 kg of CO_2. Concrete building systems such as insulating concrete forms and tilt-up concrete incorporate insulation and thermal mass energy efficient wall systems that save energy over the life of a building resulting in significantly lower CO_2 emissions related to building occupancy when compared to wood and steel frame construction. Another research study compared the CO_2 emissions of concrete and steel framed buildings on a per-square-meter basis and showed that concrete produced 550 kg of CO_2 per square meter of floor area and steel produced 620 kg of CO_2 per square meter of floor area.[10]

More importantly, as discussed earlier, concrete wall and floor systems such as insulating concrete forms, tilt-up concrete, precast concrete, and concrete masonry incorporate insulation and thermal mass that saves energy over the life of a building resulting in significantly lower CO_2 emissions related to building occupancy when compared to wood and steel frame construction. In one research study comparing energy performance of various concrete wall systems to wood frame and steel frame structures, concrete wall systems reduced energy requirements for a typical home by more than 17%. By comparison, a stick-frame house will have to be built with 2x12 lumber and R-38 insulation to achieve the same energy performance as the insulated concrete wall comprised of 6 inches of concrete and two layers of 2-inch thick rigid insulation.[12]

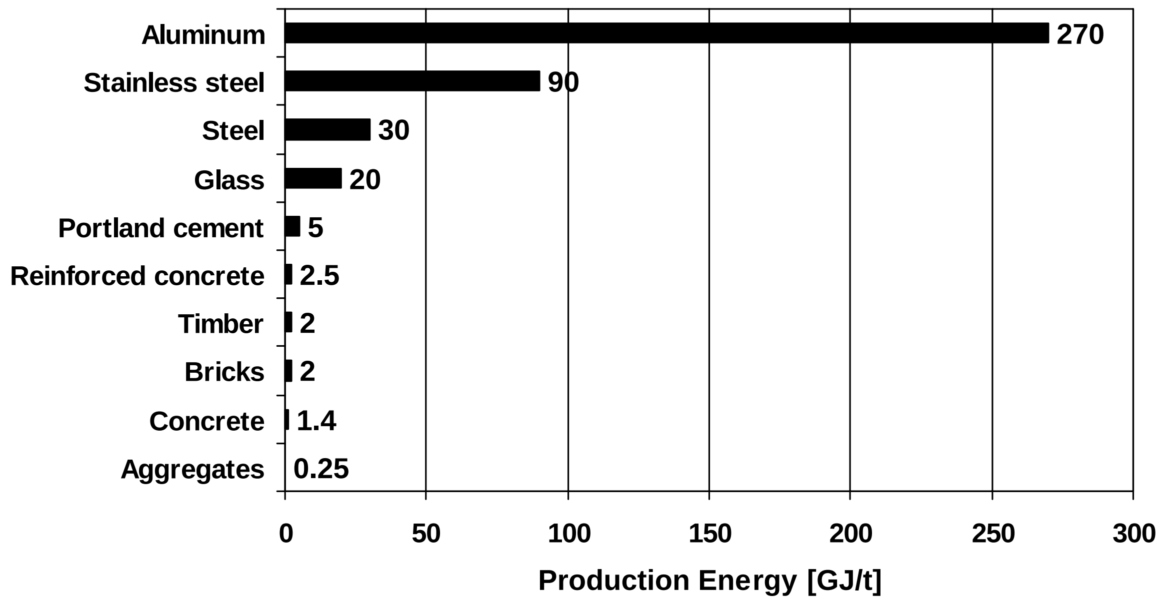

FIGURE 3 - ENERGY OF PRODUCTION FOR CONCRETE AND OTHER COMMON BUILDING MATERIALS

Regardless of its low impact relative to other building materials, the concrete industry is committed to constant environmental improvement through process innovation and product standards that lead to reduced environmental impact. The U.S. concrete industry has implemented the P2P Initiative (Prescriptive to Performance Specifications for Concrete) which provides concrete producers with more flexibility to optimize concrete mixtures for intended performance that will also reduce environmental impact, including CO_2 emissions. [11]

Traditionally, construction specifications for concrete have required unnecessarily high quantities of portland cement along with other limits on the use of supplementary cementitious materials. Many of these limits are incorporated into codes and specifications. The P2P Initiative proposes to eliminate many of these limits and evolve to performance based standards that will result in greater use of industrial byproducts such as fly ash, blast furnace slag, and silica fume to supplement a portion of the cement used in concrete. These supplementary cementitious materials, work in combination with portland cement to improve strength and durability in addition to reducing the CO_2 embodied in concrete by as much as 70% with typical values ranging between 15 and 40%.

SUMMARY

Table 2 summarizes the ways concrete can contribute toward points *LEED-NC*. The RMC Research and Education Foundation has developed the Ready Mixed Concrete LEED Reference Guide to assist engineers, architects, and concrete producers understand how concrete contributes to LEED certification. The guide includes strategies for achieving LEED points in each of the categories listed in Table 2 and suggestions for achieving Innovation in Design credits.

Credit category	Credit number and name		Points
Sustainable Sites	Credit 3	Brownfield Redevelopment	1
	Credit 5.1	Site Development: Protect or Restore Habitat	1
	Credit 5.2	Site Development: Maximize Open Space	1
	Credit 6.1	Stormwater Design, Quantity Control	1
	Credit 7.1	Heat Island Effect, Non-Roof	1
	Credit 7.2	Heat Island Effect, Non-Roof	1
Energy and Atmosphere	Prerequisite 2	Minimum Energy Performance	not appl.
	Credit 1	Optimize Energy Performance	0 to 4
Materials and Resources	Credit 1.1	Building Reuse: Maintain 75% of Existing Walls, Floors & Roof	1
	Credit 1.2	Building Reuse, Maintain 95% of Existing Walls, Floors & Roof	1
	Credit 2.1	Construction Waste Management, Divert 50% from Disposal	1
	Credit 2.2	Construction Waste Management, Divert 75% from Disposal	1
	Credit 4.1	Recycled Content, 10% (post-consumer + ½ pre-consumer)	1
	Credit 4.2	Recycled Content, 20% (post-consumer + ½ pre-consumer)	1
	Credit 5.1	Regional Materials: 10% Extracted, Processed & Manufactured Regionally	1
	Credit 5.2	Regional Materials: 20% Extracted, Processed & Manufactured Regionally	1
Innovation and Design Process	Credit 1.1	Innovation in Design, Reduce Cement Content	1
	Credits 1.2-1.4	Apply for other credits demonstrating exceptional performance	3*

*Up to 3 additional points can be earned: documentation must be submitted and approved (not included in total above)

TABLE 2 - POSSIBLE POINTS FOR CONCRETE IN LEED-NC VERSION 2.2

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