CONCRETE SUSTAINABILITY REPORT
NATIONAL READY MIXED CONCRETE ASSOCIATION CSR02—JUNE 2010

Concrete and Climate Change:

How Does Concrete Stack Up Against Other Building Materials?

By Lionel Lemay, P.E., S.E, LEED AP, Senior VP, Sustainable Development, NRMCA
Colin Lobo, P.E., Ph.D., Senior VP, Engineering, NRMCA

Climate change or global warming is the increase in the average temperature of the Earth's atmosphere and oceans as a result of the buildup of greenhouse gases in the atmosphere. Greenhouse gases can be released by natural events, such as volcanic eruptions and anthropogenic (human) activities such as deforestation, and more so by burning fossil fuels to manufacture products, power vehicles and generate energy to heat and cool buildings. Livestock, agriculture, landfill emissions and use of chlorofluorocarbons in refrigeration systems are additional sources of greenhouse gases resulting from human activity.

Carbon dioxide is one of several greenhouse gases that are attributed to global warming by trapping the Sun's radiant energy in our atmosphere. This process is called the greenhouse effect. In general, carbon dioxide, or CO_2, is exhaled by humans and animals and utilized by plants during photosynthesis. Additionally, carbon dioxide is generated by the combustion of fossil fuels or plant matter, among other chemical processes. Greenhouse gases include water vapor (36-66%), carbon dioxide (9-26%), ozone and other minor greenhouse gases (7-8%), with their approximate range of influence on the greenhouse effect in parentheses. On an equal concentration basis, some greenhouse gases, such as methane and nitrous oxides, have a greater impact on the greenhouse effect than carbon dioxide, but since they have significantly lower concentrations in the Earth's atmosphere they have less impact on the greenhouse effect. Water vapor, the most abundant greenhouse gas, is not affected by human activity.[1]

Atmospheric concentrations of CO_2 are expressed in units of parts per million by volume (ppm). Since the beginning of the Industrial Revolution in the late 1700s, the concentration of CO_2 in Earth's atmosphere has increased by about 100 ppm (from 280 ppm to 380 ppm (Figure 1.)[2] The first 50 ppm increase occurred from the start of the Industrial Revolution in 1773 to around 1973; the next 50 ppm increase took place from 1973 to 2006. It is estimated that 64% of the CO_2 added to the atmosphere since 1850 is due to burning fossil fuels and this accounts for approximately 14% of the CO_2 in the atmosphere.[3]

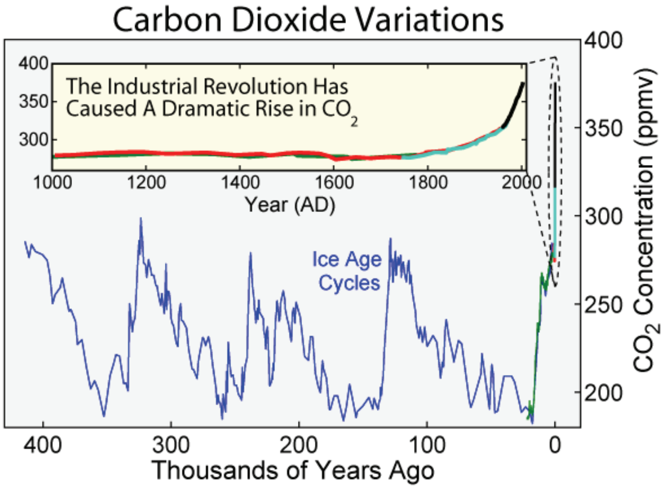

Figure 1. CO_2 Concentrations in Earth's atmosphere during the last 400,000 years.

Many scientists believe that global warming will cause a rise in sea level, increase the intensity of extreme weather, and change the amount and pattern of precipitation. Other effects could include changes in agricultural yields, glacier retreat, species extinctions and increases in disease. These effects could severely impact the Earth's ability to support life. Many scientists

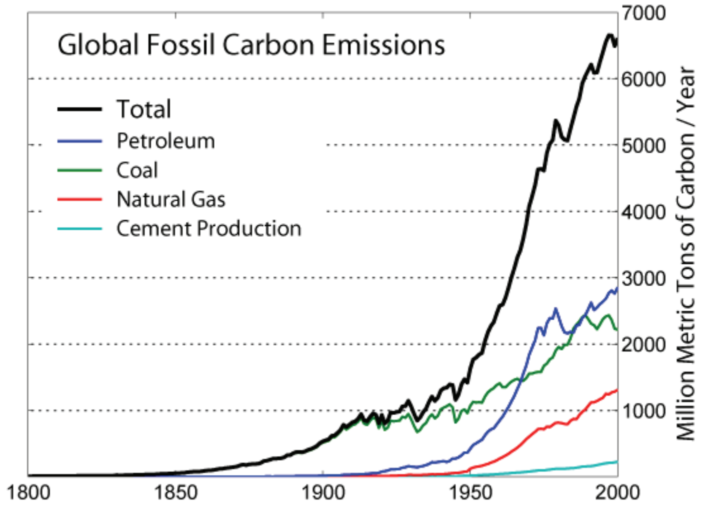

Figure 2. Global annual fossil fuel carbon dioxide emission compared to cement manufacture

believe recently observed global warming is partially caused by greenhouse gas emissions from energy production, transportation, industry and agriculture.

Energy and Emissions

Energy consumption and carbon dioxide emissions, both measures of environmental impact, are important parameters in the discussion of life cycle assessment (LCA.) LCA attempts to quantify the environmental impacts, including energy consumption and carbon emissions, of a product, process or service. LCA is sometimes used to measure the environmental impact of structures throughout their entire life cycle. Generally, a building or building product life cycle can be divided into five life cycle phases: material acquisition, manufacturing, construction, operational phase, and demolition, reuse or recycling.

The operational phase is typically the longest and most critical phase of the life cycle since this includes the actual use of the product in a building or roadway. Impacts from heating and cooling buildings, roadway traffic, maintenance and repair typically far outweigh the impacts during the other four life cycle phases. There are few published works that take into account all five phases when conducting a comparative LCA of concrete and other building materials. The research studies referenced in this paper are mainly partial LCAs for several different phases of the life cycle.

CO2 from Cement Manufacturing As with all industrial processes, cement manufacturing requires energy and the subsequent generation of CO_2. According to the U.S. Department of Energy, cement production accounts for 1.8% of energy consumed in the U.S. This level is relatively low in comparison with other industries, such as petroleum refining at 31.4%, steel production at 4.9% and wood production at 2.1%.[4] For the most part, CO_2 is generated from two different sources during the cement manufacturing process:

1) use of fossil fuels in the burning process, and
2) calcination, when calcium carbonate is heated and broken down to calcium oxide with the release of CO_2.

Calcium oxide is approximately 60% of the raw material required for the manufacture of cement. Limestone is the primary naturally occurring source of calcium oxide used in the manufacture of cement.

A comparison of CO_2 emissions from burning fossil fuels to that from cement production is illustrated in Figure 2.[5] On average, 927 kg (2044 lb) of CO_2 are emitted for every 1000 kg (2205 lb) of portland cement produced in the U.S.[6] This quantity of CO_2 emission is directly related to the amount of clinker in finished portland cement.

The U.S. cement industry accounts for approximately 1.5% of U.S. CO_2 emissions, well below other major sources such as heating and cooling residences (21%), heating and cooling commercial buildings (19%), transportation (31%) and industrial operations (29%) (Figure 3.)[7]

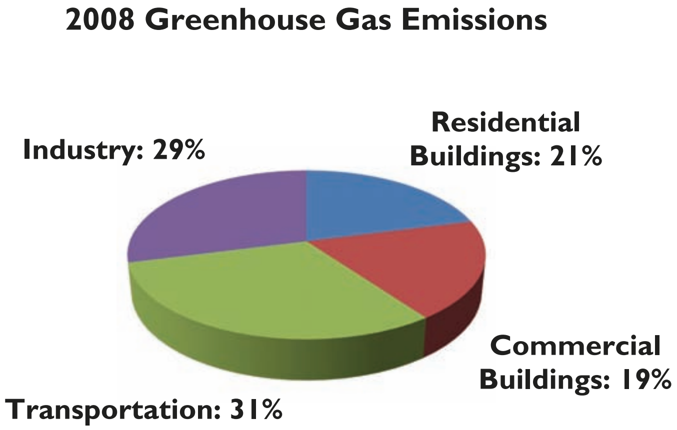

Figure 3 – 2008 U.S. greenhouse gas emissions by sector

Embodied CO_2 in Concrete The carbon footprint of concrete compares favorably with other building materials. The benefits of concrete have been documented in its ability to provide a longer service life and help reduce the carbon footprint of buildings and pavements during their operational phase. Recycling and reuse of concrete at the end of the service life of a structure is also common practice.

Concrete, in its basic form, is composed of cement, water and aggregates. Water, sand, stone or gravel, and other ingredients make up about 90% of the volume of concrete mixtures (Figure 4.) The process of mining sand and gravel, crushing stone, combining the materials in a concrete plant and transporting concrete to the construction site requires comparatively very little energy and therefore only emits a relatively small amount of CO_2 into the atmosphere. The amounts of CO_2 embodied in concrete are primarily a function of the cement content in concrete mixtures.

Concrete uses between about 7% and 15% cement by mass depending on the performance requirements for the concrete. The average quantity of portland cement is around 250 kg/m^3 (420 lb/yd^3). This average quantity has consistently decreased with better optimization of concrete mixtures and increased use of supplementary cementitious materials (SCMs) that can improve the strength and durability characteristics of concrete. As a result, approximately 100 to 300 kg of CO_2 is embodied in every cubic meter of concrete (170 to 500 lb per yd^3) produced or approximately 5% to 13% of the weight of concrete produced, depending on the mixture proportions.

It is also documented that a significant portion of the CO_2 produced during cement manufacturing is reabsorbed into concrete during the product's life cycle through a natural process called carbonation. A Norwegian 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]

Concrete Versus Other Materials

Concrete compares favorably to other building materials such as steel, wood and asphalt when analyzing energy consumption and CO_2 emissions. Concrete building systems such as insulating concrete forms (ICFs) and tilt-up concrete incorporate insulation, high thermal mass and low air infiltration to create energy efficient wall systems that save energy over the operational phase of a building. The result is significantly lower CO_2 emissions related to building occupancy when compared to wood and steel frame construction.

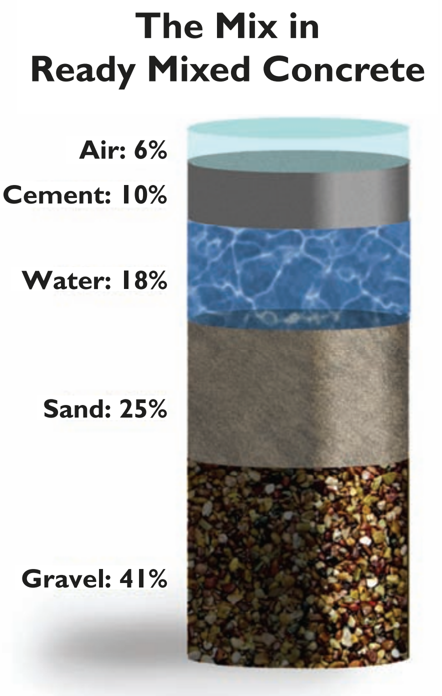

Figure 4. Typical composition of concrete by volume.

One research study, conducted by CTLGroup, compares energy performance of various concrete wall systems to wood frame and steel frame for a typical residential structure in various climate zones. In this study concrete wall systems resulted in reduced energy requirements by more than 17%. By comparison, to achieve similar energy performance, a wood-frame house would have to be built with 2x12 (50 mm x 300 mm) lumber and R-38 insulation to achieve the same energy performance as an insulated concrete wall system comprised of 150 mm (6 in) of concrete and two layers of 60 mm (2 in) thick rigid insulation.[9]

Another research study by the same group compared the energy cost of a steel framed building with lightly framed exterior walls to that of a concrete framed building with concrete exterior walls to determine the benefit of thermal mass. The analysis was conducted for six different cities in the U.S. Energy savings during the operational phase for the concrete frame building were 5% in Miami, 10% in Phoenix, 16% in Memphis, TN, 18% in Chicago, 21% in Denver, and 23% in Salem, OR.[10]

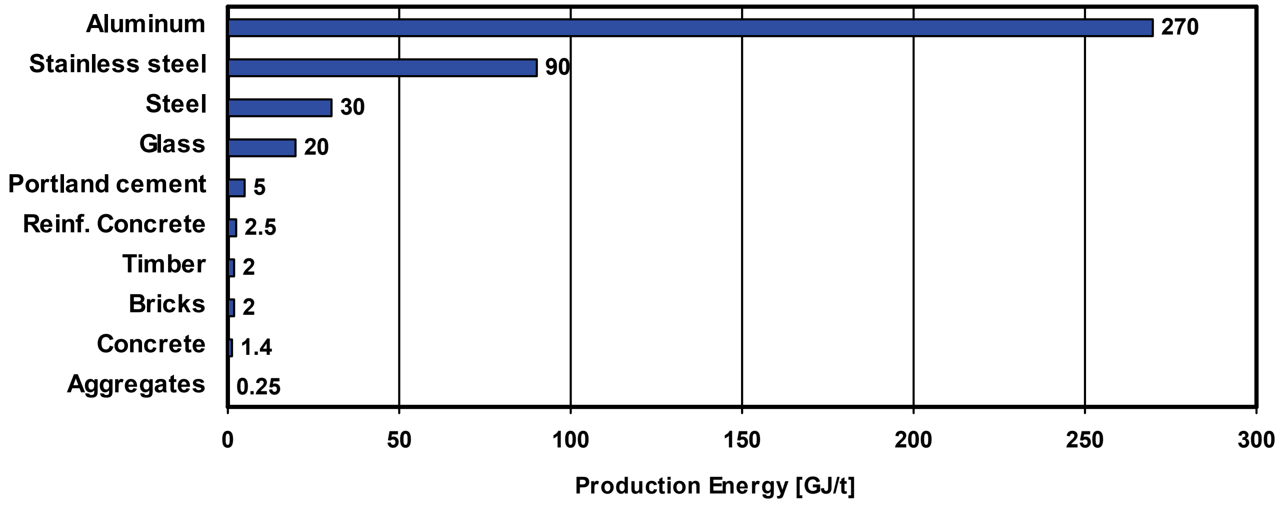

Figure 5. Energy of production for common building materials.

To evaluate the energy required to build structures and the relative carbon footprint, Pentalla compared common building materials for raw material extraction, transportation and manufacturing. The study concluded that the energy required to produce reinforced concrete was 2.5 GJ/t (2.2 million BTU/ton) compared to 30 GJ/t (25.8 million BTU/ton) for steel and 2.0 GJ/t (1.7 million BTU/ton) for wood (Figure 5).[11]

Guggemos and Horvath compared the embodied CO_2 in concrete and steel framed buildings on a unit area basis. They concluded that concrete accounted for 550 kg of CO_2 per square meter of floor area (112 lb/ft^2) and steel accounted for 620 kg of CO_2 per square meter of floor area (127 lb/ft^2) for the building they investigated.[12]

When it comes to residential and commercial buildings, the material extraction, product manufacturing and construction phase generates a very small portion of its carbon footprint during its entire life cycle. The major portion of the carbon footprint is the operational phase where heating, air conditioning, and appliances generate most of the CO_2 throughout a structure's lifetime. Gajda and VanGeem report that approximately 98% of the CO_2 emissions from a residence were from the use of natural gas appliances throughout its 100-year lifetime. Only about 2% was attributed to the material extraction, manufacturing and construction phase.[13]

Studies conducted by National Resources Council of Canada compared fuel consumption and emissions for a 100 km (62 mi) section of a major urban arterial highway, one paved with asphalt and the other paved with concrete. These studies concluded that heavy trucks traveling on concrete pavement accumulate statistically significant fuel savings, ranging from 0.8% to 6.9%, with an average of 3.85%. These fuel savings can lead to reductions in greenhouse gas emissions as summarized in Table 1.[14,15] The fuel savings come from the fact that concrete pavements are stiffer than asphalt pavements and as a result offer less resistance to rolling.

The University of Texas at Arlington investigated the differences that might exist in fuel consumption and CO_2 emissions when operating an automobile on asphalt pavement versus a concrete pavement under city driving conditions. Two pairs of street sections, one asphalt and one concrete, with similar gradients and roughness were selected for fuel consumption comparisons. The study concludes that driving on concrete pave-

Annual Fuel Savings and CO_2 Emission Reductions from Driving Trucks on Concrete Pavements versus Asphalt Pavements for a Major Arterial Highway	
Average Savings 3.85%	
Fuel Savings	**18,130 l/ km (7,708 gal/mi)**
CO_2 Reductions	**50 t/ km (88 tons/mi)**

Table 1. Annual fuel savings and CO_2 emission reductions from driving trucks on concrete versus asphalt pavement for a major urban arterial highway.

ments can reduce fuel consumption by 3% to 17%, resulting in significant cost savings, fuel savings and reduction in CO_2 emissions. For example, if the annual vehicle miles travelled in the Dallas-Fort Worth region in Texas took place at a constant speed of 50 km/h (30 mph) on concrete pavements similar to those in the study, the annual fuel savings would be 670 million liters (177 million gallons) and the annual CO_2 reduction would be 620,000 tonnes (680,000 tons.)[16]

Athena Institute conducted a life cycle analysis on concrete and asphalt roadways to compare embodied energy and global warming potential for construction and maintenance over a 50-year life cycle. The study concluded that for a high volume highway, the asphalt pavement alternative required three times more energy than its concrete pavement counterparts from a life cycle perspective. For a high volume roadway, asphalt generated global warming potential of 738 t/km (1309 tons/mi) of CO_2 equivalents compared to 674 t/km (1196 tons/mi) of CO_2 equivalent for concrete.[17]

Concrete pavements can also reduce energy demand for lighting since concrete is more reflective than darker pavements. This is because fewer lighting fixtures (or lower wattage fixtures) are needed to provide the same illumination on a roadway built with concrete instead of asphalt. Stark demonstrated that a concrete roadway would use 31% less energy as a result of using fewer lighting fixtures.[18]

Research at Lawrence Berkeley National Laboratory shows that the consistent use of light-colored, high-mass building materials such as concrete for structures and pavements, along with strategic landscaping, can help reduce urban heat islands. An urban heat island is a metropolitan area which is significantly warmer than its surrounding rural area. Temperatures in residential zones can rise by as much as 1.7 ºC (3 ºF) and in downtown areas by as much as 3.9 ºC (7 ºF), primarily because of dark-colored roofing and pavements.

According to the research, the use of light- and heat-reflective materials, along with careful planting of trees, could lower the average summer afternoon temperature in some cities by as much as 2.8 ºC (5 ºF), cutting the need for air conditioning by 18%. Since air-conditioners use electricity, primarily generated from coal-fired electric power plants, reducing urban heat islands can reduce energy consumption and related greenhouse gas emissions considerably.[19]

Sustainability Initiatives

Cement Industry The cement industry was among the first to tackle the issue of energy and emissions that impact climate change. Since 1975, the cement industry has reduced emissions by 33%. Portland Cement Association members adopted a voluntary Code of Conduct, (principles, performance measures, and a reporting protocol) to support the Cement Manufacturing Sustainability Program. By the year 2020, the industry plans to voluntarily reduce CO_2 emissions by 10%, energy use by 20% and cement kiln dust by 60% from a 1990 baseline.[20]

As indicated, the CO_2 emissions associated with the manufacture of cement is generated from burning fossil fuels and from the calcination of limestone, among other ingredients, to produce clinker. Therefore, the primary options for reducing the quantity of CO_2 generated from manufacturing cement are to use alternatives to fossil fuels, non-carbonate sources of calcium oxide as a raw ingredient in manufacture and to intergrind additional materials with the clinker. Besides 5% gypsum that is needed to control cement setting characteristics, limestone and mineral processing additions are interground with clinker in the manufacture of portland cement. These can amount to between 3 to 10% of the finished cement as currently permitted by ASTM C150, Standard Specification for Portland Cement. Specifications in Europe and Canada permit larger quantities. Intergrinding or blending SCMs like fly ash, slag cement and silica fume to manufacture blended cements are additional ways to reduce the clinker content in finished cement.

Blended cement use in the U.S. is approximately 3% of the total cement shipments which is considerably lower than other countries. The European Ready Mixed Concrete Organization reports that the blended cement used by its members is approximately 30% of the total cement used. However, in the U.S., concrete producers add supplementary SCMs when producing concrete as it affords the flexibility for various applications and seasonal adjustments to concrete mixtures. Regardless of whether SCMs are interground with cement clinker by the cement manufacturer to produce blended cements or added to concrete mixtures at the concrete plant, the result is the same: a reduced carbon footprint.

The ability to intergrind limestone and mineral processing additions in portland cement are more recent revisions to cement standards ASTM C150 and AASHTO M85. Both permit up to 5% of limestone as interground material in finished cement.

This level of interground limestone has no impact on product performance. It is estimated, based on an annual U.S. cement production of 110 Mt (120 million tons), that at an average use of 2.5% interground limestone in finished cement will reduce CO_2 emission by more than 2.3 Mt (2.5 million tons) per year. Annual energy reductions have been estimated at 13,000 GJ (12 billion BTU) from lower fuel use and 190 million kWh from lower electricity consumption.[21] Using interground limestone in cement is already common practice in Europe and Canada.[22] Recently, cements with interground limestone up to 15% by mass have been approved as a cement type in Canada.

The cement industry has also consistently increased its use of non-fossil based fuels in cement manufacture. These include spent solvents from other industries, waste tire-derived fuels, etc. Some of these efforts have been constrained by local regulations.

NRMCA Sustainability Initiatives

Vision

The vision of the ready mixed concrete industry is to transform the built environment by improving the way concrete is manufactured and used in order to achieve an optimum balance among environmental, social and economic conditions.

Objectives

The concrete industry will be a leading player in helping society build infrastructure to support our desired standard of living and achieve a built environment that will minimize negative impacts on our planet's natural environment. The concrete industry will continue to listen, observe, research, reflect, consult and collaborate with all stakeholders to achieve its vision.

To fully realize this vision, the concrete industry will approach sustainable development through the life cycle perspective. Concrete's life cycle phases include material acquisition, production, construction, use (operations and maintenance), and recycling. It has and will continue to evaluate all phases of its product life cycle in order to reduce its environmental footprint. It has and will continue to evaluate each phase of the life cycle to employ strategies for reducing environmental impact with the following objectives:

- Minimize Energy Use
- Reduce Emissions
- Conserve Water
- Minimize Waste
- Increase Recycled Content

Key Performance Indicators

The concrete industry intends to measure and report annually its progress toward meeting its sustainability goals. Progress will be measured on a per unit of product basis and compared to 2007 levels. Key performance indicators are:

- Embodied energy: 20% reduction by 2020, 30% reduction by 2030
- Carbon footprint: 20% reduction by 2020, 30% reduction by 2030
- Potable water: 10% reduction by 2020, 20% reduction by 2030
- Waste: 30% reduction by 2020, 50% reduction by 2030
- Recycled content: 200% increase by 2020, 400% increase by 2030

Table 2. NRMCA Sustainability Initiatives

Concrete Industry The U.S. concrete industry is committed to continuous environmental improvement through process innovation and product standards that lead to reduced environmental impact. National Ready Mixed Concrete Association (NRMCA) members have implemented the P2P Initiative (Prescriptive to Performance Specifications for Concrete) that attempts to change specifications for concrete by reducing the level of prescription and allow concrete producers more flexibility to optimize concrete mixtures for their intended performance. This, when adopted by a design professional, will also reduce environmental impact, including CO_2 emissions.

Traditionally, construction specifications for concrete have required unnecessarily high quantities of portland cement along with other maximum limits on the use of SCMs. These limits are incorporated in the industry's standards and specifications. The P2P Initiative proposes to eliminate many of these limits and evolve to performance-based requirements for strength and durability of concrete. Progress on these fronts will reduce the environmental impact of concrete as a building material.[23]

The U.S. concrete industry uses a significant amount of industrial byproducts such as fly ash, ground granulated blast furnace slag (slag cement) and silica fume as a portion of the cementitious material in concrete. In 2008 the U.S. electric power industry generated a total of about 123.5 Mt (136.1 million tons) of coal combustion byproducts of which approximately 45% was used in construction and industrial processes. The cement and concrete industry used 16.6 Mt (18.3 million tons) of fly ash in 2008.[24]

The use of slag cement as an SCM has increased significantly resulting in large reductions in CO_2 emissions attributable to a concrete mixture. Besides use as a cementitious material, iron slags are used as raw feed in cement manufacture and aggregates in concrete mixtures. The U.S. Geological Survey estimates that between 15 Mt (16.5 million tons) of iron blast furnace slag was produced in the U.S. in 2008 of which 2.7 MT (3.0 million tons) was used in concrete as an SCM.[25,26]

NRMCA has adopted initiatives to enhance the overall sustainability of ready mixed concrete. The NRMCA Sustainability Initiatives set a vision, goals and strategies for reducing embodied energy, carbon footprint, water use and waste, and for increasing the recycled content of ready mixed concrete (Table 2.)[27] NRMCA intends to establish measurements for various aspects of concrete production and document their progress toward meeting these sustainability goals. Progress will be measured on a per unit of production basis compared to 2007 levels. The concrete industry incorporates a variety of environmental best management practices in the production of its product. These include the reuse and recycling of waste from concrete manufacture such as water and unused returned concrete. It also incorporates waste byproducts from other industries such as recycled industrial waste water, foundry sands, glass and other materials that would typically end up in landfills.

Conclusion

The cement and concrete industry has an impact on the carbon footprint of the built environment. In evaluating the five phases of the environmental life cycle of buildings and pavements, concrete performs well when compared to other building materials. However, as it relates to sustainable development there are always opportunities for improvement. As with any building product, concrete and its ingredients do require energy to produce which in turn produces carbon dioxide or CO_2. The amount of CO_2 produced during the manufacturing process is relatively small when compared with other building materials and when compared with the operational phase of buildings and pavements. The cement and concrete industry has established ambitious goals for reducing carbon footprint of the manufacturing process and providing products that can improve the carbon footprint of the built environment.

References

1. *Water vapour: feedback or forcing?* RealClimate, http://www.realclimate.org/index.php?p=142.
2. Image by Robert A. Rohde, Global Warming Art, http://www.globalwarmingart.com.
3. Carbon Dioxide Information Analysis Center, http://cdiac.ornl.gov/pns/faq.html.
4. 2006 Energy Consumption by Manufacturers, U.S. Energy Information Administration, http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html.
5. Image from Global Warming Art, http://www.globalwarmingart.com.
6. Marceau, M. L., Nisbet, M. A., and VanGeem, M. G. Life Cycle Inventory of Portland Cement Manufacture, SN2095b, Portland Cement Association, Skokie, IL, 2006.
7. Emissions of Greenhouse Gases in the United States 2008, U.S. Department of Energy, December 2009, http://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/ggrpt/057308.pdf.
8. Pade, C. *et al.* The CO_2 Uptake of Concrete in the Perspective of Life Cycle Inventory, International Symposium on Sustainability in the Cement and Concrete Industry, Lillehammer, Norway, September 2007.
9. Gajda, J. Energy Use of Single-Family Houses With Various Exterior Walls, CD026, Portland Cement Association, Skokie, IL, 2001.

10. Marceau, M. L. and VanGeem, M. G. Modeling Energy Performance of Concrete Buildings for LEED-NC Version 2.2: Energy and Atmosphere Credit 1, SN2880a. Portland Cement Association, Skokie, IL, 2007.
11. Pentalla, V. Concrete and Sustainable Development, ACI Materials Journal, September-October 1997, American Concrete Institute, Farmington Hills, MI, 1997.
12. Guggemos, A. A. and Horvath, A. Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings, ASCE Journal of Infrastructure Systems, June 2005.
13. Gajda, J., VanGeem, M. G. and Marceau, M. L. Environmental Life Cycle Inventory of Single Family Housing, SN2582a, Portland Cement Association, Skokie, IL, 2002.
14. Taylor, G. W. Additional Analysis of the Effect of Pavement Structures on Truck Fuel Consumption, National Research Council of Canada (NRC), Ottawa, Ontario, 2002.
15. Taylor, G. W. and Patten, J. D. Effects of Pavement Structure on Vehicle Fuel Consumption - Phase III, National Research Council of Canada, Ottawa, Ontario, 2006.
16. Ardekani, S. A. and Sumitsawan, P. Effects of Pavement Type on Fuel Consumption and Emissions in City Driving, RMC Research & Education Foundation, Silver Spring, MD, 2010.
17. A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy And Global Warming Potential, Athena Institute, Ottawa, Ontario, 2006.
18. Stark, R. E. Road Surface's Reflectance Influences Lighting Design, Lighting Design + Application, April 1986.
19. Rosenfeld, A. H. *et al.* Painting the Town White—and Green, MIT Technology Review, February/March 1997.
20. 2007 Report on Sustainable Manufacturing, Portland Cement Association, Skokie, IL, 2007, http://www.cement.org/smreport07/index.htm.
21. Hawkins, P., Tennis, P. D., and Detwiler, R. J. The Use of Limestone in Portland Cement: A State-of-the-Art Review, Portland Cement Association, EB227, Skokie, IL, 2003.
22. Nisbet, M. The Reduction of Resource Input and Emissions Achieved by Addition of Limestone to Portland Cement, Report to Portland Cement Association, PCA R&D Serial No. 2086, November 1996.
23. National Ready Mixed Concrete Association, P2P Initiative, http://www.nrmca.org/P2P.
24. 2008 Coal Combustion Product (CCP) Production & Use Survey Report, American Coal Ash Association, http://www.acaa-usa.org.
25. Iron and Steel Slag Statistics, U.S. Geological Survey, U.S. Department of the Interior http://minerals.usgs.gov.
26. U.S. Slag Cement Shipments, Slag Cement Association, http://www.slagcement.org.
27. NRMCA Sustainability Initiatives, National Ready Mixed Concrete Association, http://www.nrmca.org/sustainability.