CONCRETE SUSTAINABILITY REPORT
NATIONAL READY MIXED CONCRETE ASSOCIATION CSR03—FEBRUARY 2011

The Sustainability of Concrete Pavements

By Lionel Lemay, P.E., S.E., LEED AP, Senior VP, Sustainable Development, NRMCA
Erin Ashley, Ph.D., LEED AP, Senior Director, Sustainable Construction, NRMCA

Our economy depends on transportation infrastructure. We drive to work and school on roads each day. Most of our food, clothing and consumer products are delivered in trucks that travel our interstate highway system. Businesses rely on roads and runways to transport materials and parts needed to manufacture the products we use every day. Families rely on these same roads and runways to visit friends and family or to take vacations. And, when we reach our destinations, we rely on driveways and parking areas to park our cars and trucks. We even rely on sidewalks to get us where we're going.

Our transportation infrastructure connects our communities. Without it, we would not be a productive society. However, this interconnecting network of roads, runways, parking areas and sidewalks does have an impact on our environment. The same cars, trucks and airplanes that support our economy also use energy, emit greenhouse gases and other air emissions, and can place a significant toll on surrounding ecosystems. The construction process, including material manufacturing, can also place a burden on the environment. Therefore, when we build new transportation infrastructure or repair and maintain existing infrastructure, it makes sense to use design strategies and building materials that minimize environmental impact.

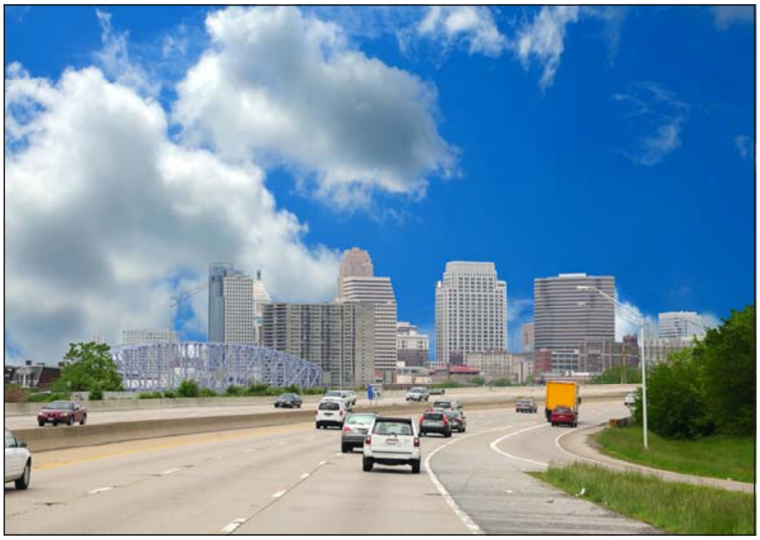

Figure 1. Our economy depends on transportation infrastructure. We drive to work and school on roads each day. Most of our food, clothing and consumer products are delivered in trucks that travel our interstate highway system.

What Makes a Pavement Sustainable?

Pavements should have a long service life and require little maintenance. They should minimize energy consumption and greenhouse gas emissions. They should be resource efficient by using local materials and incorporating recycled products. One way to accomplish these objectives is to use concrete pavements. Concrete pavements can be used to build new or replace existing sidewalks, driveways, parking lots, local streets and roads, highways and runways. Concrete pavements can be designed economically to carry light loading, such as pedestrians and passenger vehicles, all the way up to the heaviest trucks and airplanes. Concrete can also be used to repair deteriorated asphalt pavement with a product called whitetopping or concrete overlay. Other products such as pervious concrete, that allows rainwater to pass through it, can help reduce and treat stormwater.

When evaluating environmental impacts, it is important to look at the entire life cycle of a product or project. Looking at one phase of the life cycle, such as material extraction, manufacturing or construction, and ignoring the operation or use phase may not result in the most efficient design. This paper explores how concrete pavements can improve our transportation infrastructure and minimize environmental impacts throughout all phases of a pavement's life cycle, including material extraction, manufacturing, construction, use (operations and maintenance) and recycling/reuse/disposal.

Durability

Excessive wear and tear on vehicles is directly related to the quality of roads. According to the Federal Highway Administration (FHWA), for federally funded highways, including the national highway system and other arterials and collectors eligible for federal funding, the vehicle miles travelled on pavements with good ride quality was only 47% in 2006.

Figure 2. Our transportation infrastructure, including roads, runways, parking lots and sidewalks, connects our communities and sustains our vibrant economy.

In addition, congestion continues to increase and clog America's roadways, costing taxpayers billions of dollars and billions of wasted hours. According to FHWA, the estimated percentage of travel occurring under congested conditions rose from 24.9% to 28.7% from 1997 to 2005. The average length of time motorists spend in congested conditions increased from 5.9 hours per day in 1997 to 6.4 hours per day in 2005.[1]

Americans spend more than 4.2 billion hours per year stuck in traffic, costing $78.2 billion per year in wasted time and fuel. Thirty-two percent of America's major roads are in poor or mediocre condition. Driving on roads in need of repair costs American motorists $67 billion annually in extra vehicle repair and operating costs, which amounts to over $324 per motorist. The problem continues to rise as vehicle travel on America's highways increased by 39% from 1990 to 2008, while new road mileage increased by only four percent.[2]

Providing durable, long lasting roadways that require little maintenance can reduce the wear and tear on our cars and trucks and decrease the congestion on our roadways. Concrete pavements are durable and as a result they generally have longer service lives than asphalt pavements. There are many examples of concrete pavements with service lives of 50 years or longer.[3] Concrete pavements do not require rehabilitation or reconstruction as often as asphalt pavements and as a result the life cycle cost of concrete pavements are lower and losses in productivity as a result of lane closers are reduced.

Lower Embodied Energy

The embodied energy of a material refers to the energy needed to extract, process and refine it for its intended use. Thus, a correlation exists between the number and type of processing steps and the embodied energy of a material. For example, the fewer and simpler the extraction, processing and refining steps involved in a material's production, the lower its embodied energy. The embodied energy of a pavement is the total energy required to extract materials from the ground, process these materials, produce the pavement, construct the pavement, provide maintenance over the specified time period, and recycle or demolish the roadway at the end of its specified life.

The Athena Institute studied the embodied energy and global warming potential of concrete and asphalt roads 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 counterpart from a life cycle perspective. For a high volume roadway, asphalt generated global warming potential of 738 t/km (1,309 tons/mi) of CO_2 equivalents compared to 674 t/km (1,196 tons/mi) of CO_2 equivalent for concrete. The study did not take into account addition fuel savings or energy savings from lighting as described later in this paper that would further reduce the embodied energy and CO_2 equivalents associated with concrete pavements.[4]

Fuel Savings

Several research studies have shown that driving on concrete pavements uses less fuel and as a result, lowers carbon emissions and other associated emissions when compared to asphalt pavements. Although the reasons are not completely understood, the theory is that because concrete pavements are considerable stiffer than asphalt pavements they deflect less when subjected to vehicle loading. This means that a car or truck traveling on a more flexible pavement absorbs part of the vehicle energy that would otherwise be available to propel the vehicle forward, thus requiring more fuel.

The studies have shown that trucks demonstrate fuel savings when driven on concrete highway pavements versus asphalt highway pavements. Fuel consumption for cars is not influenced by pavement type for highways presumably because cars are lighter in weight and the deflections are such that they do not affect fuel consumption significantly. However, one study shows that cars traveling on city streets do demonstrate lower fuel consumption on concrete pavements compared to asphalt pavements. It is assumed that because the pavement cross sections are thinner for concrete streets that deflections caused by passenger vehicles are large enough that they do affect fuel consumption.

Zaniewski conducted one of the earliest fuel consumption studies commissioned by FHWA in 1982. In this study, fuel consumption data was collected for different vehicle types, pavement designs, pavement conditions, and pavement grades and curvatures. Twelve highway sections were tested, some concrete and some asphalt. Vehicles were driven at different speeds ranging from 16 to 112 km/h (10 to 70 mph) and fuel consumption was accurately measured while other variables, including pavement roughness, remained constant.

The test results indicate that fuel consumption for trucks, ranging from 2-axle pickup trucks to 4-axle semi-trailer trucks, at speeds greater than 32 km/h (20 mph), was lower for concrete highway pavements then for asphalt highway pavements. The difference in fuel consumption was as much as 0.85 km/l (2 mpg.) The semi-trailer truck in this study had fuel consumption of approximately 1.91 km/l (4.5 mpg) on asphalt pavement and 2.33 km/l (5.5 mpg) on concrete pavement, meaning the average savings was approximately 20% for semi-trailer trucks.[5]

Another comprehensive study of fuel consumption was conducted by the National Research Council of Canada with reports published in 2002 and 2006. Semi-trailer trucks were driven on highway pavements in Ontario and Quebec

SI Units					
% Fuel Savings	Fuel Saved (l)	Fuel Savings ($)	CO_2 Equiv. (t)	NO_x (kg)	SO_2 (kg)
0.8 minimum	550.4	$440.32	1.51	17.18	2.17
3.85 average	2,648.8	$2119.04	7.31	82.68	10.45
6.9 maximum	4,747.2	$3797.76	13.09	148.18	18.73

US Customary Units					
% Fuel Savings	Fuel Saved (gal)	Fuel Savings ($)	CO_2 Equiv. (tons)	NO_x (lbs)	SO_2 (lbs)
0.8 minimum	145.4	$440.32	1.66	37.88	4.78
3.85 average	699.8	$2119.04	8.06	182.28	23.04
6.9 maximum	1,254.2	$3797.76	14.43	326.68	41.29

Table 1. Annual potential fuel savings, cost savings and reduction in CO_2, NO_x, SO_2 if a semi-trailer operated a total of 160,000 km/year (99,419 mi/year). It is assumed the semi-trailer truck has a fuel consumption of 2.33 km/l (5.47 g/mi) and an average cost of diesel fuel of $0.80 per liter ($3.02 per gallon).

comparing fuel consumption for asphalt and concrete pavements. Variables studied in the analysis included pavement roughness, load, speed, season, temperature, grade and wind. Onboard state-of-the-art real time computerized data collection equipment was used in the semi-tractor trailer unit to collect and calculate instantaneous fuel flow while traveling over the different pavements.

The semi-trailer data was analyzed using a multivariate linear regression analysis tool to determine the potential savings and the statistical significance of the results. The results of the 2002 study showed statistically significant fuel savings for trucks operating on concrete pavements over asphalt pavements ranging from:

- 4.1% to 4.9% savings on concrete pavement at 100 km/h (62 mph)
- 5.4% to 6.9% savings on concrete pavement at 60 km/h (37 mph)

The results of the 2006 study shows statistically significant fuel savings for trucks traveling on concrete pavements over asphalt pavements ranging from:

- 0.8% to 1.8% savings on concrete pavement at 100 km/h (62 mph)
- 1.3% to 3.9% savings on concrete pavement at 60 km/h (37 mph)

Based on these studies, Table 1 shows the annual potential fuel savings, cost savings and reduction in CO_2, NO_X, SO_2 if a semi-trailer truck operated a total of 160,000 km/year (99,419 mi/year). It is assumed the semi-trailer truck has a fuel consumption of 2.33 km/l (5.47 g/mi) and an average cost of diesel fuel of $0.80 per liter ($3.02 per gallon).[6,7]

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 street pavements versus concrete street pavements 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 pavements reduced 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).[8]

Reduced Lighting Requirements

Darkness increases the potential for accidents. The fatality rate is approximately three times greater during the nighttime than during the daytime, when adjusted for vehicle traffic volumes. Therefore, in busy traffic areas, it makes sense to add artificial lighting to reduce accidents. However, lighting is expensive to install, maintain and operate. In a 1986 paper by Stark, the initial cost of purchasing and installing light fixtures for a typical roadway can range from $54,370 to $96,313 per kilometer ($87,500 to $155,000 per mile.) This is based on an estimated cost per light fixture of approximately $4,000. The Stark report also estimates the cost to operated roadway lighting to range between $1,367 and $2,485 per kilometer ($2,200 and $4,000 per mile) per year for energy and between $1,616 and $2,858 per kilometer ($2,600 and $4,600 per mile) per year for maintenance. All dollar figures have been adjusted for inflation.

Concrete pavements can reduce the initial costs, maintenance costs and energy demand for lighting since concrete is more reflective than darker pavements. Fewer lighting fixtures, or lower wattage fixtures, are needed to provide the same illumination on a roadway built with concrete. Stark demonstrated that a concrete roadway would use 31% less

Figure 3. Reflectance of concrete pavements (left) are higher than asphalt pavement (right) resulting in safer pavements and reduced energy consumption.

energy and associated greenhouse gas emissions as a result of using fewer lighting fixtures and could reduce initial cost and maintenance costs by similar amounts.[9]

Reduced Urban Heat Islands

Research at Lawrence Berkeley National Laboratory shows that the consistent use of light-colored pavements along with strategic landscaping and light colored roofing, can help reduce urban heat islands. An urban heat island is a metropolitan area which is significantly warmer than its surrounding rural area because of roofs and pavements that are baked by the sun and warm air. In many large cities, temperatures in residential zones can rise by as much as 1.7 °C (3 °F) and in downtown areas by as much as 3.9 °C (7 °F), primarily because of dark-colored roofing and pavements. The increased temperatures can cause discomfort, hike air-conditioning bills and accelerate the formation of smog. Cities in all climate zones, such as Los Angeles, Chicago, Washington and Atlanta, along with many other U. S. cities are subject to the urban heat island effect.

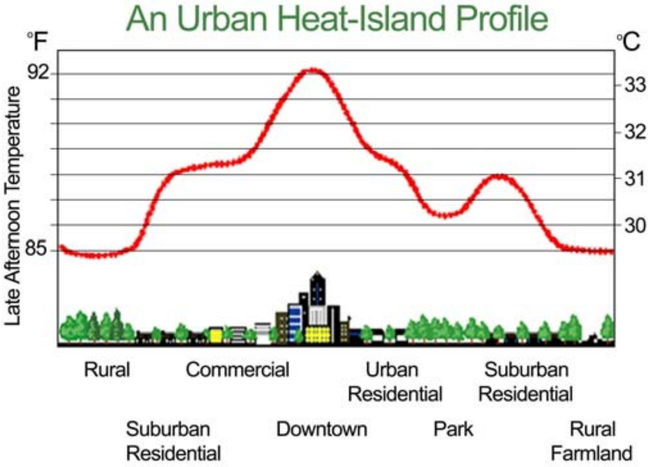

Figure 4. Fewer trees, along with dark colored roofing and pavements cause the heat island effect, raising temperatures in urban and suburban areas.

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 °C (5 °F), 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.

Counter intuitively, using light colored roofing and pavements can also benefit cities in the north. For example, in New York City, the length of the day in December is half that of a day in June. Also, the sun is so low in the sky that it shines on only half the roof or pavement area in December versus June. In addition, New York experiences three times more cloudy days in the winter than in the summer. When you multiply these three factors (1/2 x 1/2 x 1/3 = 1/12) the potential for horizontal surfaces to absorb the suns energy is only 1/12 in December as in June. This means that because so little sun ever reaches roofs and pavements in the winter months the benefits of lowering temperatures in the summer far outweighs raising temperatures in the winter.[10]

Stormwater Management

Pervious concrete is a performance-engineered concrete with a 15-30% void system that allows rainwater to percolate through it. When pervious concrete is used for parking areas, streets, plazas and walkways it minimizes stormwater runoff to surrounding streams and lakes and allows for natural filtration to recharge local groundwater supplies.

Figure 5. Pervious concrete is used for parking areas, streets, plazas and walkways to help minimize stormwater runoff to surrounding streams and lakes.

Pervious pavement is especially compelling as a leading edge green building technology and is recognized by the U.S. Environmental Protection Agency (EPA) as a recommended Best Management Practice (BMP) for stormwater management that supports the principles of Low Impact Development (LID).

Pervious concrete has been documented as eliminating stormwater runoff and improving water quality.

In addition to the stormwater management benefits of pervious concrete, it can also act to reduce the heat island effect by absorbing less heat from solar radiation than darker pavements. The relatively open pore structure and the light color of pervious concrete stores less heat, therefore, helping to lower heat island effects in urban areas. Kevern, et al, have shown that pervious concrete stores less energy, therefore less heat, when exposed to sun over an extended period of time. This heat is not reflected back to the environment resulting in lower external temperatures. Lower external temperatures of the pavement result in a reduction of the heat island effect.[11]

Recycling and Reuse

Concrete incorporates recycled materials in several different ways. The most widely used recycled products in concrete are Supplementary Cementitious Materials (SCMs) such as fly ash, slag cement and silica fume. In 2007, the concrete industry consumed over 26 million tonnes (28.66 million tons) of these industrial byproducts that would otherwise end up in landfills. SCMs are the key to high performance concrete. When combined with cement in concrete they improve durability, strength and constructability. In the case of highways, streets and parking areas, durability is the number one concern. Fly ash, slag and silica fume are used to enhance durability by decreasing permeability and cracking. They help block migration of chloride ions to reinforcing steel, the most common cause of corrosion.

The environmental benefits of using these industrial byproducts in concrete means a reduction in the amount of waste materials sent to landfills, reduced raw materials extracted, reduced energy of production and reduced emissions, including CO_2. Fly ash is the byproduct of burning coal in electric power plants. Generally, 15% to 20% of burned coal takes the form of fly ash. At one time, most fly ash was landfilled, but today a significant portion is used in concrete. Blast furnace slag is the byproduct of steel manufacturing. After grinding, the blast furnace slag takes on much higher value as a cementitious material for concrete. Blast furnace slag can be used as a partial replacement for cement to impart added strength and durability to concrete. Silica fume is a byproduct of processing quartz into silicon metals in an electric arc furnace. They are superfine, spherical particles that when combined with cement significantly increases strength and durability of concrete. It is used heavily for bridge and parking decks to produce concretes that are extremely durable.

The greatest opportunity for recycling lies in crushing concrete for various applications after demolition. After decades, or sometimes centuries of use in a building or pavement, concrete can be crushed and reused. The Construction Materials Recycling Association estimates that 127 million tonnes (140 million tons) of concrete are recycled annually. Recycling concrete from demolition can be used for aggregate base for new pavements and some crushed concrete can be recycled as aggregate into new concrete. Recycling old concrete as aggregate protects natural resources by reducing the demand for virgin aggregate materials and eliminates the need to dispose of it into landfills. The same basic equipment used to process virgin aggregates is used to crush, size, clean and stockpile recycled concrete aggregates. Ideal uses include fills and bases, roadways and parking areas, driveways and sidewalks, shoulders, curbs and gutters, landscaping features, foundations and some concrete structures, including pavements.

According to an FHWA study, 38 states recycle concrete as aggregate base and 11 recycle it into new concrete.[12] In one example, recycled concrete aggregate was used for Interstate 5 Improvements in Anaheim, California. Crushed concrete from

Figure 6. Recycled industrial byproducts such as fly ash, slag and silica fume (inset) are used to enhance durability of concrete by decreasing permeability and cracking.

the demolition of the existing roadway was stockpiled for reuse as base material for the new roadway. The highway improvement project consumed all 635,029 tonnes (700,000 tons) of recycled concrete generated from the demolition and an additional 90,718 tonnes (100,000 tons) of recycled aggregate was brought in to complete the project. Using the recycled aggregate saved Caltrans approximately $5 million over purchasing and hauling virgin aggregate and disposing of the demolition debris.[13]

Life Cycle Assessment

Life cycle assessment (LCA) is a technique for assessing impacts associated with a product or process. LCA's are usually accomplished using complex computer models that take into account every impact throughout all life cycle phases, from cradle to grave, for the product or process being evaluated. For pavements, life cycle phases include material extraction, manufacturing, construction, use (operations and maintenance), and recycling/reuse/disposal. For most pavements, the use phase has the greatest impact on the overall footprint since it includes the impacts of fuel consumption and emissions from cars and trucks, along with the energy and emissions as a result of maintenance, lighting and the urban heat island effect.

The process of conducting an LCA involves compiling an inventory of energy and material inputs and environmental impacts such as emissions to water and air, ozone depletion, global warming, acidification, eutrophication, photochemical smog, human health risks, ecotoxicity, fossil fuel use, land use and water use. The goal of LCA is to compare all the environmental, social, and economic damages to help make informed decisions about how to change the process to reduce impact.

The science of LCA is relatively new and few full LCA's have been conducted for pavements. The Massachusetts Institute of Technology (MIT), a leader in the field of LCA, has released initial reports of research efforts that will help set a new standard for LCA modeling. Researchers are working to quantify the full cradle to grave life cycle environmental and economic impacts of pavements and buildings. What is setting the MIT research apart from other research is that more effort is being placed on identifying the impacts of operating and maintaining pavements over a 50-year life cycle.

An interim report issued in December 2010 suggests that for high-volume roads (major highways), the use phase can account for as much as 85% of the carbon emissions. Based on previous research on fuel consumption conducted by others, there is a potential for significant fuel savings on concrete pavements over asphalt pavements that could lead to substantially lower life cycle carbon emissions. In addition, varying scheduled maintenance and associated lane closures can reduce CO_2 emissions for concrete pavements over the life cycle of the pavement.

As work continues, MIT will supplement the ongoing environmental LCA work with economic analyses using life-cycle-cost analysis (LCCA). The research will provide the scientific and design community, industry leaders and policymakers with a much clearer understanding of the real life environmental and economic costs of building and paving materials.

Conclusions

Transportation infrastructure connects our communities and is a critical component to a vibrant economic system in the U.S. However, transportation is a large consumer of energy and emitter of greenhouse gases. One way to improve the overall environmental performance of our transportation infrastructure is to use concrete pavements since:

- Concrete pavements are durable and last longer
- Concrete pavements require less maintenance and fewer repairs
- Concrete pavements take less energy to build
- Cars and trucks traveling on concrete pavements consume less fuel
- Concrete pavements need less lighting
- Concrete's light color helps reduce urban heat islands
- Concrete is made from local and abundant materials
- Concrete uses significant amount of recycled materials
- Concrete is recyclable

All these features of concrete pavements help reduce energy consumption, greenhouse gas emissions and resource depletion attributed to our transportation infrastructure. For more information on the sustainability of concrete, visit www.nrmca.org/sustainability.

References

1. U.S. Department of Transportation, 2008 Status of the Nation's Highways, Bridges and Transit: Conditions and Performance, Report to Congress, Executive Summary, http://ntl.bts.gov/lib/33000/33400/33453/2008StatusSummary.pdf, accessed February 2011.
2. The Road Information Project (TRIP), Key Facts About America's Surface Transportation System and Federal Funding, http://www.tripnet.org/Fact_Sheet_National.pdf, accessed February 2011.
3. Wathne, L., and T. Smith. Green Highways: North American Concrete Paving Industry's Perspective, 10th International Symposium on Concrete Roads, September 18–22, 2006, Brussels, Belgium.
4. A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential, Athena Institute, 2006.
5. Zaniewski, J. P., Effects of Pavement Surface Type on Fuel Consumption, SR289.01P, Portland Cement Association, Skokie, Illinois, 1989.
6. Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption, Prepared for Government of Canada Action Plan 2000 on Climate Change, G. W. Taylor Consulting, Woodlawn, Ontario, 2002.
7. Taylor, G. W. and Patten, J. D. Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III, National Research Center of Canada, Ottawa, Ontario, 2006.
8. 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.
9. Stark, R. E., Road Surface's Reflectance Influences Lighting Design, Lighting Design + Application, April 1986.
10. Rosenfeld, A. H. et al. Painting the Town White—and Green, MIT Technology Review, February/March 1997.
11. Kevern, J. T., Schaefer, V. R., and Wang, K. Temperature Behavior of a Pervious Concrete System, National Transportation Research Board of the National Academies, Transportation Research Record: Journal of the Transportation Research Board, Volume 2098 / 2009.
12. Recycled Concrete Aggregate, Federal Highway Administration National Review, http://www.fhwa.dot.gov/pavement/recycling/rca.cfm, accessed February 2010.
13. Construction Materials Recycling Association, http://www.concreterecycling.org/histories.html, accessed May 2010.
14. Massachusetts Institute of Technology Concrete Sustainability Hub, http://web.mit.edu/cshub/news/pdf/PavementsLCAsummaryDec2010.pdf, accessed February 2011.

National Ready Mixed Concrete Association
900 Spring Street, Silver Spring, Maryland 20910
888-846-7622 | www.nrmca.org