Green Highways

Environmentally and Economically Sustainable Concrete Pavements

concrete pavement research and technology *special report*

Contents

ACPA
American Concrete Pavement Association

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Introduction

The concepts of "sustainability" and "sustainable development" are receiving much attention as the causes of global warming and climate change are debated. The World Commission on Environment and Development has defined sustainable development as "meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs" (report to the United Nations General Assembly, August 1987).

In 2005, the U.S. Environmental Protection Agency (EPA) started the Green Highways Initiative as an instrument for coordinating transportation and environmentalism. According to this initiative, "green highways" are those that are environmentally responsible and sustainable in all aspects, including design, construction, and maintenance.

A major focus of the initiative is to demonstrate and ensure that sustainable practices in pavements can go hand in hand with economic success. This is indeed true of concrete pavements.

Particularly because of its long life, concrete is an economical, cost-effective pavement solution that consumes minimal materials, energy, and other resources for construction, maintenance, and rehabilitation activities over its lifetime. Beyond longevity, other features of concrete pavement further enhance its sustainability:

- Properly constructed and textured concrete pavements have reduced pavement deflection, which results in reduced vehicle fuel consumption.
- The construction of concrete pavements consumes less fuel (particularly diesel) during materials production, transportation, and placement than the construction of asphalt pavements.
- Concrete pavement mixtures incorporate industrial byproducts (i.e., fly ash and slag cement), which lowers the disposal needs, reduces the demand on virgin materials, and conserves natural resources.
- Concrete pavement itself is renewable and 100% recyclable.
- Concrete pavement requires less subbase aggregate materials for structural support than asphalt pavements.
- Concrete pavements' lighter color and increased reflectivity improve nighttime visibility, reduce the amount of power needed to illuminate roads at night, and help mitigate urban heat island and smog generation.
- Concrete pavements exhibit a lower energy footprint associated with their production, delivery, and maintenance than asphalt pavements do over a predetermined time period.
- Concrete pavements designed with pervious concrete shoulders minimize surface-water discharge and help replenish groundwater aquifers.
- Optimized concrete pavement surface textures produce quieter pavements over longer periods of time, reducing noise pollution.

Although cement is a relatively energy-intensive and carbon dioxide (CO_2)-intensive material to manufacture, it is important to recognize that cement manufacturing accounts for only 1.5% of

U.S. CO_2 emissions; the balance of emissions comes from sources such as electricity production (40%), transportation (33%), residential heating (6%), and various other commercial and industrial processes (DOE 2006).

Furthermore, it is critical to recognize that cement is only one of the materials that make up the final product—concrete. Figure 1 illustrates how 92% of the volume of typical paving concrete is comprised of materials that require very little energy to obtain and have a low CO_2 footprint, including sand, gravel, water, air, and industrial byproducts.

In addition, the cement industry has taken dramatic steps to reduce any environmental impact of the manufacturing process, reducing the amount of energy to make a ton of product by more than 33% since 1972. The Cement Manufacturing Sustainability (CMS) Program continues this success with a national pledge to reduce CO_2 emissions by an additional 10% per ton of product by 2020, from a 1990 baseline.

The overall positive effects of reducing energy use and minimizing the environmental footprint of development through efficient and sustainable use of concrete dramatically outweigh the impact of the cement manufacturing process (Carter 2006). Put another way, concrete is one of the world's most CO_2-efficient and sustainable building materials.

The rest of this report provides more information about the features of concrete pavements that contribute to their legacy as a cost-efficient, sustainable, and green choice for highway pavements.

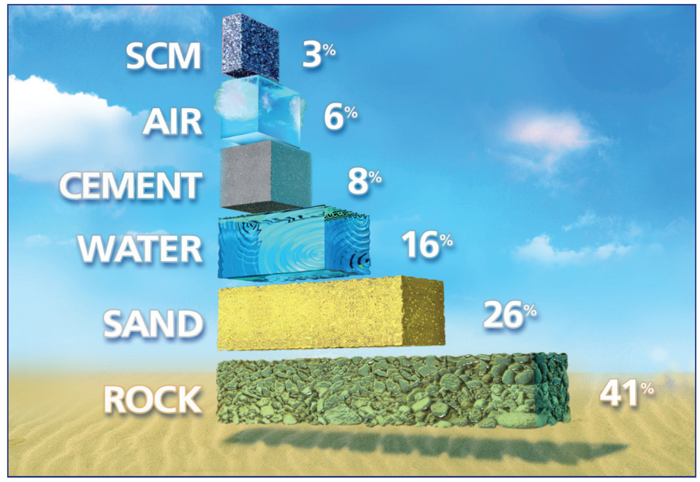

Figure 1. Concrete constituents

Longevity

The longevity of concrete pavements is well documented. Numerous concrete highways in North America have lasted 50 years or more, supporting traffic volumes much greater than originally anticipated. Such long-lasting concrete pavements are not confined to one region of North America, nor to a specific type of environment or climate. A few notable U.S. examples are provided here:

- Interstate 10 in the San Bernardino Valley in California was originally constructed in 1946 as part of Route 66. Portions of this concrete highway are still carrying traffic today at an impressive volume of more than 200,000 vehicles per day. After being renewed three times by surface grinding during its more than 60-year life, this highway is a true testament to concrete pavement's sustainability (ACPA 2006).
- US 52 in Charleston, South Carolina, which local residents call Rivers Avenue, has provided Charleston residents with uninterrupted service for more than 50 years. A two-mile (3 km) section of this east–west thoroughfare was paved with concrete in the early 1950s and has required little in terms of maintenance since.
- Belknap Place, one of the first concrete streets in San Antonio, Texas, was paved with concrete in 1914. It is still performing well today, 92 years after it was constructed (Taubert 2006).
- Route 23 through Kanabec County, Minnesota, was originally paved with concrete in 1948. According to a Minnesota Department of Transportation (DOT) pavement condition survey conducted in 2000, the 52-year old concrete pavement still has a present serviceability rating[†] (PSR) of 4.1 (Very Good).
- More than half of the concrete pavements older than 50 years remaining in Minnesota have a PSR greater than 3.1 (corresponding to ratings of Good or Very Good) (Wathne and Smith 2006).

Such long-lived concrete pavements have demonstrated economic advantages in terms of life-cycle costs. In addition, they contribute directly to the system's sustainability in several important ways.

A long-lasting concrete pavement does not require rehabilitation or reconstruction as often, and therefore consumes less raw materials in the long run. This longevity impacts our environment in other ways as well. Energy savings are realized, since rehabilitation and reconstruction efforts consume energy. Also, congestion is reduced (with accompanying energy savings and reduction in vehicle pollutants) by employing long-lasting concrete pavements because of fewer construction zones impeding traffic flow.

[†]The PSR is an index of pavement roughness measured on a scale from 0.0–5.0, where a higher value corresponds to a better pavement condition.

Because of this longevity, concrete pavements have the potential to help society address the challenges of sustainable development in numerous ways. Ultimately, all these environmental and social benefits add up to greater long-term economic benefits to the public.

Reduced Vehicle Fuel Consumption and Emissions

Profile stability is a term used to describe the ability of a pavement surface to resist deformation and deflection caused by sustained and repeated loading. Unlike asphalt pavement, which is viscoelastic and therefore sensitive to both temperature and loading, concrete pavement's rigid surface does not deform under heavy vehicle loading and therefore deflects less. This not only makes concrete pavement less susceptible to the formation of heavy-vehicle wheel ruts and the associated increased hydroplaning potential, it also positively impacts vehicle fuel consumption.

Fuel consumption is partly a function of the degree to which a pavement deflects in response to the load applied as the wheels of heavy vehicles traverse the surface. Any deflection absorbs some of the energy that would otherwise be available to propel the vehicle forward.

Several studies to date suggest that the resistance (amount of deflection) encountered by heavy-vehicle wheels on asphalt pavements is measurably greater than resistance on concrete pavements (Figure 2). Thus, more energy and more fuel are required to move heavy vehicles on flexible pavements (Taylor Consulting 2002).

The most in-depth studies into this phenomenon were conducted in several phases over multiple years by the National Research Council of Canada (NRC). The final study included collaboration between Natural Resources Canada (NRCan) and the Cement Association of Canada, with input from various departments of transportation. The studies concluded that tractor-trailers traveling on concrete pavements have statistically significant lower fuel consumption than those traveling on asphalt pavements throughout the

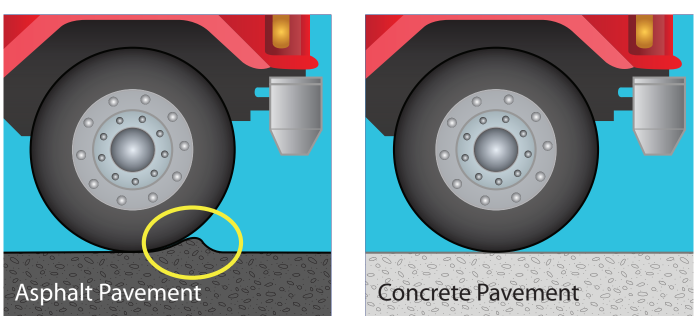

Figure 2. Exaggerated depiction of a truck tire rolling on asphalt (left) and concrete (right)

summer to winter temperature range for fully loaded trucks operating on smooth pavements [IRI < 120 in./mi (1,900 mm/km)].

The findings from these studies (Taylor Consulting 2002; Taylor and Patten 2006) are illustrated in Figure 3 and Tables 1 and 2. Figure 3 shows that fuel consumption for two common truck types—tractor tanker semi-trailer and tractor van semi-trailer—can be reduced an average of about 1% to 6% when traveling on concrete versus asphalt pavement, depending on truck type and vehicle speed. These savings were used to calculate the potential economic and environmental benefits from tractor-trailers traveling on concrete pavement compared to asphalt pavement, as shown in Tables 1 and 2.

Table 1 identifies the potential yearly savings for the maximum, minimum, and average percent diesel fuel saved in dollars, carbon dioxide, nitrogen oxides, and sulfur dioxide if one tractor-trailer unit traveled 100,000 miles (160,000 km) in a year. For the calculations, it is assumed that the tractor-trailer unit has an average engine fuel consumption of 5.5 miles per gallon (43 liters per 100 km) and that diesel fuel costs $2.99 per gallon ($0.79 per liter).

Table 2 identifies the potential yearly savings for a major arterial highway that is 62 miles (100 km) long and car-

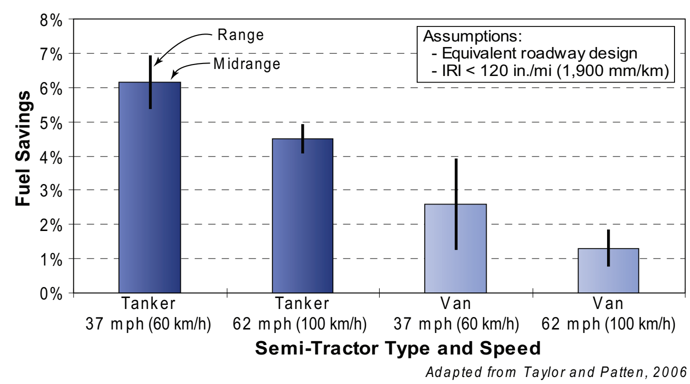

Figure 3. Fuel savings with concrete versus asphalt pavement

Table 1. Yearly potential savings in cost, CO_2, NO_X, and SO_2 per tractor trailer

Fuel Savings (%)	Fuel Saved [gal (l)]	Fuel Cost Saved (dollars)	CO_2 [tons (metric tons)]	NO_x [lb (kg)]	SO_2 [lb (kg)]
Minimum: 0.80	145 (549)	$435	1.66 (1.50)	37.2 (16.9)	4.80 (2.18)
Average: 3.85	700 (2,650)	$2,100	8.06 (7.31)	182 (82.6)	23.0 (10.4)
Maximum: 6.90	1,250 (4,730)	$3,760	14.4 (13.0)	327 (148)	41.3 (18.7)

Note: CO_2 = carbon dioxide equivalent (includes carbon dioxide, methane, and nitrous oxide), NO_x = nitrogen oxides, SO_2 = sulfur dioxide.

Table 2. Yearly potential savings in cost, CO_2, NO_x, and SO_2 for a typical major arterial highway

Fuel Savings (%)	Fuel Saved [gal (l)]	Fuel Cost Saved (dollars)	CO_2 [tons (metric tons)]	NO_x [lb (kg)]	SO_2 [lb (kg)]
Minimum: 0.80	99,500 (377,000)	$298,000	1,150 (1,040)	25,900 (11,700)	3,280 (1,490)
Average: 3.85	479,000 (1,810,000)	$1,430,000	5,510 (5,000)	125,000 (56,700)	15,800 (7,170)
Maximum: 6.90	858,000 (3,250,000)	$2,570,000	9,880 (8,960)	224,000 (102,000)	28,300 (12,800)

Note: CO_2 = carbon dioxide equivalent (includes carbon dioxide, methane, and nitrous oxide), NO_x = nitrogen oxides, SO_2 = sulfur dioxide.

ries 20,000 vehicles per day with 15% trucks. Calculations assume the same tractor-trailer unit average engine diesel fuel consumption and diesel fuel cost used in Table 1.

The difference in fuel consumption as a function of pavement type should be an important consideration for government agencies when analyzing potential pavement structures for new or reconstructed pavements. Significant greenhouse gas and cost savings can be realized when operating tractor-trailers on concrete pavements versus asphalt pavements.

These environmental and economic savings can have significant down-stream implications to the public. They also play an important role in government goals to lower dependence on foreign oil and foster environmental stewardship. The emission reductions result in a direct public health benefit. The cost of consumer goods likely will be affected as well because lower fuel consumption decreases transportation expenses, which, on average, comprise nearly one-fifth of the cost of a typical consumer item.

In the context of overall transportation sustainability, these fuel savings and pollutant reductions are enormous. In the case of greenhouse gases (CO_2) alone, the average savings realized by the 62-mile (100-km) long major arterial highway in Table 2 over its 30-year design life [165,000 tons (150,000 metric tons)] are more than three times greater than the CO_2 emitted during the manufacture of cement used for the construction of the concrete pavement [52,800 tons (48,000 metric tons)]‡.

Put another way, all of the CO_2 emitted during the manufacture of cement used to construct a concrete highway pavement is compensated for during the first nine years of service by virtue of the reduced pavement deflection and improved truck fuel efficiency. The remaining 22 years of service and the proportionate CO_2 savings are a further testament to the sustainability of concrete pavements.

Lower Construction Fuel Demand

The construction of highway pavements requires a lot of energy. The production of paving materials, the transportation of these materials to the site, and their actual placement consume significant amounts of fuel, mostly diesel.

The Federal Highway Administration (FHWA) reports on fuel usage for various elements of construction, including highway paving, in its Technical Advisory T 5080.3 on Price Adjustment Contract Provisions (FHWA 1980). Attachment 1 of this Technical Advisory shows that the fuel usage factor for asphalt pavements is 2.90 gallons per ton (12 liters per metric ton), and for concrete pavements is 0.98 gallons per cubic yard (4.9 liters per cubic meter). However, as these fuel usage factors are reported in different units, it is somewhat difficult to make a direct comparison (FHWA 1980).

Table 3 converts these construction fuel usage factors to fuel required per mile of roadway constructed for asphalt and concrete. Though equivalently designed concrete pavement thicknesses are typically between two and three inches thinner than an asphalt pavement designed for the same scenario, this example conservatively assumes that the pavements have the same thickness. This example also ignores the fact that asphalt pavements typically require more layers of base granular material at a greater thickness when compared to an equivalent concrete pavement.

The table shows that the amount of fuel used per lane-mile (lane-km) of concrete roadway constructed is less than one-fifth of the fuel used to construct the same lane-mile (lane-km) of asphalt.

This means that if concrete pavements were placed instead of the roughly 500 million tons (450 million metric tons) of asphalt placed each year (FHWA 2007), the savings in diesel fuel from construction alone would amount to nearly 1.2 billion gallons (4.5 billion liters).

‡ Sample calculation for CO_2 emitted during the manufacture of cement used in the construction of a concrete highway segment:

Highway: 62 mi (100 km) long, 2 lanes wide [8 yd (7 m) total], 10 in. (250 mm) thick

Cement content in concrete mixture: 480 lb cement per cubic yard (285 kg per cubic meter)

Cement used in the concrete highway segment:

$$\frac{62 \text{ mi (100 km)} \times 1760 \text{ yd/mi (1,000 m/km)} \times 8 \text{ yd (7 m)} \times 0.28 \text{ yd (0.26 m)} \times 480 \text{ lb/yd}^3 \text{ (285 kg/m}^3\text{)}}{2{,}000 \text{ lb/ton (1,000 kg/metric ton)}} = 58{,}700 \text{ tons } (\approx 53{,}300 \text{ metric tons})$$

CO_2 emitted: 58,700 tons (53,300 metric tons) x 0.9 tons of CO_2 per ton of cement manufactured = 52,800 tons (≈ 48,000 metric tons)

Table 3. Construction fuel demand for asphalt versus concrete pavement

Pavement type	Thickness	Construction Fuel Demand
Asphalt	10 in. (250 mm)	10,718 gal (40,572 l)
Concrete	10 in. (250 mm)	1,916 gal (7,252 l)

Assumptions: Asphalt density = 140 lb/yd^3 (83 kg/m^3). Fuel usage factors: Asphalt – 2.90 gal/ton (12 l/metric ton), Concrete – 0.98 gal/cy (4.9 l/m^3) from FHWA T 5080.3, Attachment 1.

In addition to the obvious economic benefits, there are enormous environmental advantages. The savings in diesel fuel eliminates the emission of approximately 13.3 million tons (12.1 million metric tons) of CO_2 into our atmosphere each year. To put this into perspective, the average passenger car emits about five tons (4.5 metric tons) of CO_2 annually (EPA 1997). The CO_2 savings realized by constructing concrete pavements instead of the 500 million tons (450 million metric tons) of asphalt placed annually would be equivalent to taking 2.7 million cars off the road.

Use of Industrial Byproducts

In most concrete used for highways in North America, some of the portland cement is replaced or supplemented with one or more industrial byproducts. These byproducts are often referred to as supplementary cementitious materials (SCMs). The three most commonly used SCMs are fly ash (byproduct of coal burning), slag cement or ground granulated blast furnace slag (byproduct of iron production), and silica fume (byproduct of silicon or ferrosilicon alloy manufacturing).

Using SCMs in concrete pavement has several environmental benefits. First, recovering industrial byproducts avoids the use of virgin materials needed for cement manufacturing. Additionally, beneficial utilization reduces the amount disposed in landfills. More importantly, however, are the greenhouse gas and energy reductions achievable by using SCMs to replace a portion of portland cement. CO_2 and energy savings are related to the percentage of SCM used in the concrete mixture design. Many state highway agencies allow up to 25% of portland cement to be replaced with fly ash and 50% to be replaced with slag cement; some states even allow higher SCM replacement levels.

While portland cement is an essential ingredient in concrete, its production requires significant energy use and generates greenhouse gases. The cement industry in North America has made significant strides in reducing energy and emissions associated with cement manufacturing. Beyond these production technology improvements, the environmental impact of portland cement can be further reduced through partial replacement of cement with SCMs.

One study (Marceau and VanGeem 2005) showed that, for a typical Maryland DOT concrete pavement mixture, a replacement of 50% of the portland cement with slag cement resulted in a 35% reduction in embodied primary energy and a 45% reduction in embodied greenhouse gas per cubic yard (cubic meter) of concrete. This calculation includes all the energy utilized and emissions generated in mining, manufacturing and transporting concrete's constituent materials, as well as the manufacturing processes involved with producing concrete.

The EPA also recognizes the importance of SCMs in disposal, energy, and greenhouse gas reduction. Their Comprehensive Procurement Guidelines require that slag cement, fly ash, and silica fume be included in all construction project specifications utilizing federal funding (greater than $10,000), unless a valid technical or market reason for not using them can be documented.

Besides these environmental benefits, SCMs can enhance concrete properties when used in appropriate quantities. For example, they can improve workability of the mixture, decrease concrete permeability, improve durability, and enhance strength. Cost savings may also result in markets where SCMs are less expensive than portland cement, or where mixture optimization can provide engineering properties (e.g., strength or durability) that would be more expensive to achieve without SCMs.

Details on several U.S. and Canadian DOTs' allowances for the use of SCMs can be found in *A Synthesis of Data on the Use of Supplementary Cementing Materials in Concrete Pavement Applications Exposed to Freeze/Thaw and Deicing Chemicals* (Cement Association of Canada 2005), as well as in ACPA's State Practices database, accessible online at www.pavement.com.

Recyclability/Reusability

At the end of its useful life, a concrete pavement surface can be renewed via concrete pavement restoration (CPR) activities, such as full/partial depth repairs, dowel-bar retrofitting, and grinding. Diamond grinding is a particularly useful technique used to restore pavements and improve ride quality, noise, and surface texture. Studies reported by the California Department of Transportation (Caltrans) suggest that the average time before additional rehabilitation is needed for a diamond ground pavement is approximately 17 years (Stubstad et al. 2005).

Experience tells us that grinding a pavement as many as three times is possible without compromising its fatigue life. An excellent example of this is a section of I-10 (San

Bernardino Freeway) just east of Los Angeles. It was originally constructed in 1946 as part of Route 66. In 1965, it was ground to correct the considerable amounts of joint spalling and faulting that had developed during its more than 20 years of service.

This first ever continuous grinding project in North America provided 19 years of additional service. In 1984, this pavement got a third lease on life when Caltrans decided to restore the pavement again using diamond grinding. In 1997, the 51-year old pavement was ground for a third time. After more than 60 years of service, the concrete pavement is currently carrying more than 200,000 vehicles each day, a true testament to concrete pavement's sustainability (ACPA 2006).

Concrete pavement is a 100% recyclable material as well. At the ultimate end of its fatigue life, concrete pavement can be crushed and reused in many ways, for example, as granular fill, subbase material, or base course for new pavement. A 2005 study conducted by the Construction Materials Recycling Association revealed that about 130 million to 140 million tons (118 million to 127 million metric tons) of concrete were crushed and recycled in 2004.

Recycled concrete pavement can also be used as an aggregate for new concrete pavement. Some state DOTs allow up to 100% of coarse aggregate in concrete mixtures to be recycled concrete aggregate. This leads to reduced demand on nonrenewable natural resources. In addition, the short hauling distance for recycled concrete aggregate can, in some cases, reduce the cost of providing aggregate for the project. Figure 4 shows an on-site concrete pavement recycling operation.

Using recycled concrete pavement, particularly in applications that expose it to the atmosphere (e.g., embankment fill, gravel roads, roof ballast, and railroad ballast) has additional global warming benefits resulting from a process called carbon sequestering.

Approximately 60% of the CO_2 emitted during the manufacture of portland cement results from a process known as calcination, a chemical reaction among the raw materials in the cement kiln. When cement is subsequently used to produce concrete, another chemical reaction, called hydration, occurs that allows the cement to form compounds that bind the aggregates together. Later, when hardened concrete is exposed to air, the calcination reaction reverses in a process called carbonation.

In essence, carbonation recaptures CO_2. Carbonation occurs naturally in all concrete, albeit at very slow rates due primarily to the low permeability of concrete. However, exposing a large surface area of concrete to the atmosphere, typically through crushing, dramatically accelerates the carbonation process. Eventually, such exposure may allow for the recapture of all the CO_2 originally evolved from the cement raw materials during calcination (RMRC 2005).

Reduced Use of Natural Resources

Another consideration is the volume of granular base/subbase materials needed to provide structural support for pavement. Because of concrete's rigidity and stiffness, the slab itself supplies a major portion of its structural capacity and distributes heavy vehicle loads over a relatively wide area of subgrade. An asphalt pavement is not as rigid and does not spread loads as widely. Therefore, asphalt pavements usually require more layers of base granular material at a greater thickness when compared to an equivalent concrete pavement design (ACPA 2007).

Based on an analysis performed on equivalent pavement designs for asphalt and concrete pavements for an arterial

Figure 4. Paradigm in-place concrete recycling equipment in operation in Oklahoma (photo courtesy of Duit Construction)

road on a low-strength subgrade, approximately twice as much granular material is needed for an asphalt pavement structure than for a concrete structure (ARA 2003). The environmental effect of this increased demand on granular material may be amplified if suitable aggregate sources are not locally available. Longer haul distances result in aggregate haul trucks consuming more fuel and emitting more CO_2.

Light-Colored and Cool

Concrete surfaces readily reflect light. This characteristic of concrete, generally referred to as albedo, is advantageous for several reasons. It can significantly improve both pedestrian and vehicular safety by enhancing nighttime visibility on and along concrete roadways. It reduces the amount of energy needed for artificial roadway illumination during the night. It also reduces the amount of energy needed to cool urban environments, and reduces the potential for smog formation. These effects are further discussed in the following sections.

Reduced Lighting Requirement

Lighting fixtures are important elements of most urban highway facilities. Enhanced nighttime visibility is intuitively related to improved traffic safety. Figure 5, which shows highway Castello Branco in Sao Paulo state, Brazil, at night, clearly illustrates how visibility is improved in the lanes paved with concrete (ABCP 2005). In addition, because of the more reflective nature of concrete pavements, a specified luminance level can be achieved with fewer high-output lighting fixtures and standards. Ultimately, this translates to lower costs and lower energy consumption over time.

A report comparing the environmental impacts of concrete pavements to asphalt pavements indicates that asphalt pavements require more lights per unit length to achieve the same illumination as concrete pavements (Gajda and VanGeem 1997). The results suggest cost savings of as much as 31% in initial energy and maintenance costs for lighting concrete pavements versus lighting asphalt pavements. Similar results are shown in Figure 6, where energy costs required to illuminate an asphalt roadway are estimated to exceed the costs of illuminating a concrete roadway by 33%.

Heat Island Mitigation

The energy of sunlight that is not reflected off pavement surfaces is converted into thermal energy that increases the pavement's temperature. This, in turn, increases the

Figure 5. Brazil roadway illustrating concrete (left) vs. asphalt albedo

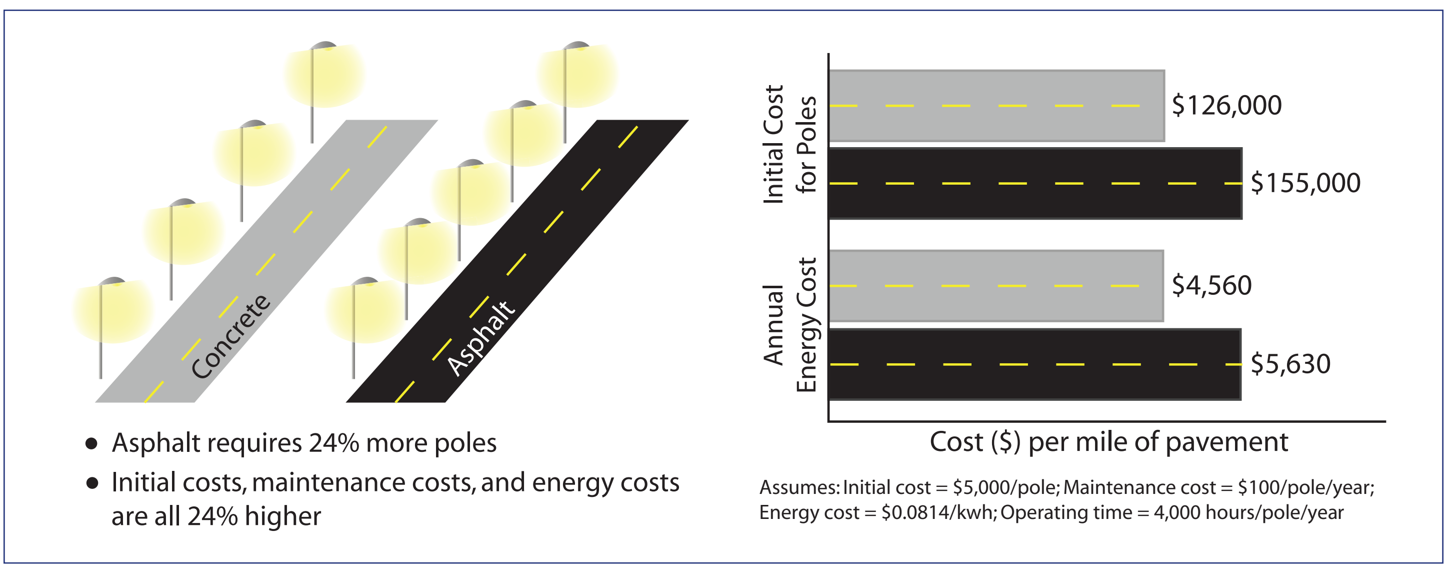

Figure 6. The need for additional light fixtures leads to higher annual energy costs for roads paved with asphalt

temperature of the air around the pavement. In urban areas, the higher air temperature that occurs as a result of pavements and other surfaces absorbing the sun's heat is known as the "heat island effect." According to some researchers, downtown areas of North American cities are up to 9°F (5°C) warmer than surrounding suburban and rural areas, where natural vegetation cools the air through evapotranspiration (Granitto 2000). Figure 7 shows an EPA illustration representing the urban heat island profile.

The heat island effect can contribute significantly to energy consumption for air conditioning to cool urban buildings. This not only consumes energy and costs money, it also leads to higher emissions from power plants. One estimate is that the increase in temperature due to heat island effects accounts for 5–10% of peak urban electric demand for air conditioning use (Akbari 2005).

Paving urban roadways with concrete is an effective strategy to help mitigate urban heat island effects. With their higher albedo, concrete pavements reflect significantly more sunlight and are cooler than asphalt pavements. Research conducted at the Lawrence Berkeley National Laboratory suggests that, when exposed to sunlight, lighter-colored concrete pavements typically have surface temperatures approximately 21°F (12°C) lower than darker-colored asphalt pavements (Pomerantz et al. 2000).

Figure 8, a thermal image of the ramp to State Road 202 in Mesa, Arizona, taken in August 2007, shows that the reduction in heat retention and emittance can be significant for brighter and more reflective concrete pavements. The thermal image illustrates the temperature difference between concrete pavement (foreground) and asphalt pavement (background) in the same ambient conditions. The picture was taken at approximately 5:00 pm during partly cloudy conditions, and the temperature difference between the two pavement surfaces was approximately 20°F (11°C).

One estimate puts the cooling energy savings from cool surfaces and shade trees, when fully implemented, at $5 billion per year in the United States alone (Akbari 2005). A 1997 report suggests that increasing the albedo of 775 miles (1,250 km) of pavement in Los Angeles (L.A.) by 0.25 (i.e., converting asphalt to concrete) would save $15 million in cooling energy each year (Pomerantz et al. 1997).

Smog Reduction

The exact effect of pavement type on heat retention and resulting air quality issues, such as smog formation, is complicated and somewhat poorly understood. However, it is clear that the process of smog formation is very sensitive to temperature.

Automobile exhaust and industrial emissions are responsible for the release of a family of NO_x (nitrogen oxide) gases and other volatile organic compounds (VOCs) as byproducts of burning gasoline and coal. On warm sunny days, these NO_x and VOCs can combine with oxygen to form ozone. Higher temperatures result in increased smog formation. Typically, at temperatures below 70°F (21°C), smog concentrations are not significant. However, at temperatures of 95°F (35°C) and above, the presence of smog is very likely. Cooling a city by only 5°F (3°C) can have a dramatic impact on smog concentration (Lawrence Berkeley Laboratories 2004).

Use of lighter-colored concrete pavements can help in this regard. Computer simulations for L.A. show that resurfacing about two-thirds of the pavements and rooftops with more reflective surfaces and planting three trees per house can lower temperatures by as much as 5°F (3°C) and can therefore significantly reduce the potential for smog formation (Akbari 2005).

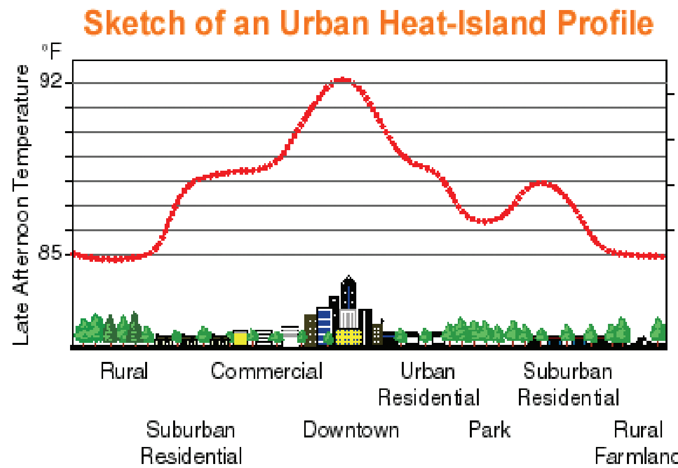

Figure 7. EPA illustration of an urban heat-island profile

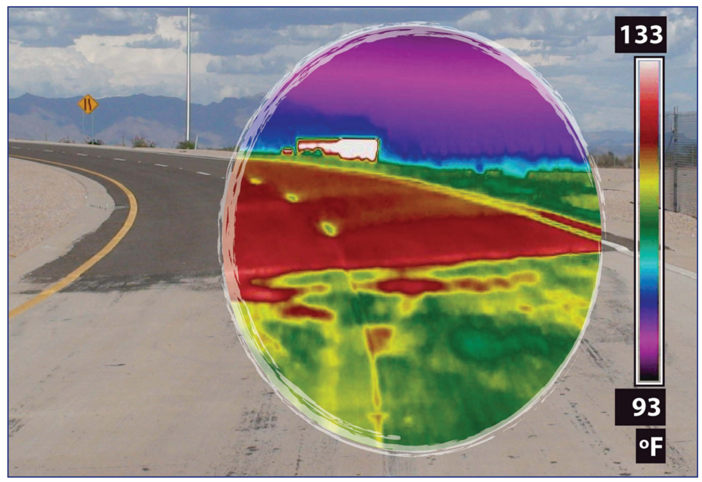

Figure 8. Thermal image of a pavement in Mesa, Arizona (note the temperature difference between the concrete pavement (foreground) and the asphalt pavement (background))

The previously mentioned Pomerantz study also found that switching the surface of 775 miles (1,250 km) of pavement in L.A. from asphalt to concrete would reduce smog-related medical and lost-work expenses by $76 million per year.

Lower Energy Footprint

Embodied primary energy is a measure of all energy use associated with the production, delivery, and maintenance of a facility over a predetermined time period. It includes both feedstock energy (the gross combustion heat value of any fossil hydrocarbon that is part of the pavement, but is not used as an energy source; e.g., bitumen) as well as primary energy (fossil fuel required by system processes including upstream energy use).

An embodied primary energy analysis in this context accounts for the energy needed to extract materials from the ground (e.g., aggregates, raw materials for cement production, oil for asphalt, etc.), process these materials, produce the paving mixtures, construct the roadway, maintain it, and rehabilitate it over a predetermined time period. This approach is an effective means to evaluate the energy footprint a facility makes during its lifetime.

A recent study conducted by the Athena Institute presents embodied primary energy and global warming estimates for the construction and maintenance of equivalent concrete and asphalt pavement structures for several different road types in various geographic regions in Canada (Athena Institute 2006). The study period was 50 years, a period that takes into account original road construction and all maintenance and rehabilitation activities for both pavement alternatives.

For all six pavement structural design comparisons, the concrete pavement alternatives clearly require significantly less energy than their asphalt pavement counterparts from a life-cycle perspective. Results show that asphalt pavements require two to five times more energy than equivalent concrete pavement alternatives. As an example, Figure 9 shows the comparative embodied primary energy for the high-volume highway pavement structures analyzed (with 0% recycled asphalt pavement (RAP) included in the final pavements). As this figure illustrates, the embodied primary energy associated with concrete pavement alternatives is only about 33% of the embodied primary energy associated with asphalt pavement alternatives.

Also evident from Figure 9 is that the feedstock energy component is the largest contributor to total energy for the asphalt pavements. However, even when feedstock energy is excluded from the analysis, concrete pavements still present a significant energy advantage over their asphalt counterparts for all pavement structures analyzed. Even with the inclusion of 20% RAP in the asphalt pave-

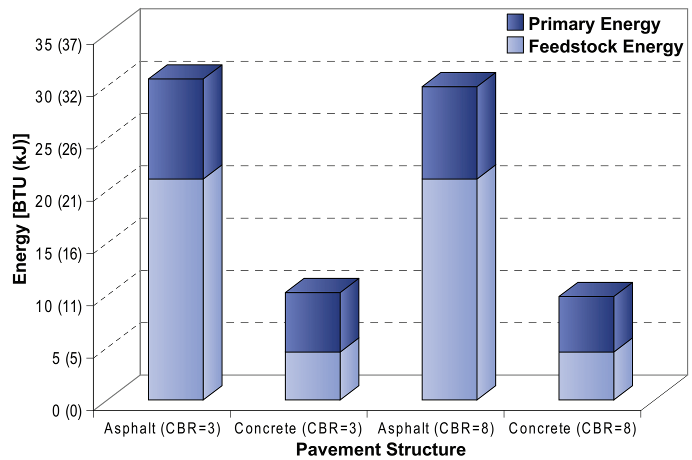

Figure 9. Comparison of embodied primary energy for high-volume roadways (0% RAP)

ment alternatives, the energy advantage of the concrete pavement counterparts is still significant, especially at the embodied energy level (Athena Institute 2006).

This study reflects the embodied energy and greenhouse gas emissions related only to production, transportation, and placement of materials for initial construction, maintenance, and rehabilitation. Operational considerations, such as truck fuel savings by operating on different pavement types (see Reduced Vehicle Fuel Consumption and Emissions on page 3) and energy savings due to the different light reflectance properties of the pavement types (see Reduced Lighting Requirement on page 7), are not considered. The report does suggest that fuel savings and urban heat island effects should be taken into account in any decisions predicated on life-cycle environmental analyses.

Improved Water Quality

Stormwater quality can be improved through the innovative use of pervious concrete pavements. Pervious concrete pavements are comprised of specially graded coarse aggregates, cementitious materials, admixtures, water, and little or no fines. Mixing these products in a carefully controlled process creates a paste that forms a thick coating around aggregate particles and creates a pavement with interconnected voids on the order of 12 to 35%. This results in a pavement that is highly permeable, with drainage rates in the range of 2.5 to 18 gallons per minute per square foot (100 to 730 liters per minute per square meter) (Brown 2003).

Pervious concrete has the potential to provide an environmentally sensitive product for specific applications. Currently, the most common uses of pervious concrete are parking lots (Figure 10), low traffic pavements, and pedestrian walkways. However, interest in its use for highway pavements and shoulders is increasing.

Figure 10. Pervious concrete pavement parking area in Normal, Illinois

Pervious concrete pavements reduce stormwater runoff and help recharge groundwater aquifers. They also reduce the amount of pollutants, such as car oil, anti-freeze, and other automobile fluids, contained in non-runoff stormwater. By allowing some rainfall to percolate into the ground, pervious concrete promotes natural filtration and "treatment" of rainwater via soil chemistry and microbial activity (Brown 2003).

Experience with pervious concrete pavements has been promising, particularly in warmer southern climates. Research in progress is addressing the freeze-thaw durability of pervious concrete to establish parameters for its durability and application as shoulders in colder climates. One research project at the National Concrete Pavement Technology Center at Iowa State University in Ames, Iowa, suggests that, with a properly proportioned mixture, freeze-thaw performance can be excellent (Kevern et al. 2005; Schaefer et al. 2006).

Clogging of pores within the concrete matrix has also been noted as a challenge of pervious paving materials. Even with significant deposition of fines within the pore structure of pervious concrete, however, the drainage rate is still sufficient to maintain flow during the majority of significant rainfall events. Routine sweeping or vacuuming of the pavement surface will remove any deposited material and restore the porosity of clogged pervious concrete to nearly new conditions.

Quiet Surface Textures

Noise pollution is a growing concern in North America. The surface texture of a highway pavement controls many important factors, including traffic noise. Noise generated at the tire–pavement interface is often the most dominant at highway speeds (TCPSC 2005).

One of the advantages of concrete pavements is that virtually any texture can be created during finishing operations, including textures that minimize tire–pavement noise while maintaining wet- and dry-weather friction for the life of the pavement.

Research by the concrete paving industry is currently underway to identify optimal textures for low noise generation at the tire–pavement interface in a variety of circumstances. In North America, a significant amount of noise issues are related to existing transversely-tined concrete pavements. Consequently, some of the ongoing research is focused on identifying diamond grinding techniques for retexturing pavement to produce the "quietest" surface textures. Research currently underway at Purdue University's Institute for Safe, Quiet, and Durable Highways is evaluating the effect of grinder blade widths and blade spacing on noise performance.

Research by the National Concrete Pavement Technology Center is looking at conventional textures in order to define construction variability (in terms of depth, width, spacing, etc.) and to develop an understanding of the relationship between three-dimensional (3D) surface texture and noise. The 3D texture is measured using a new, lightweight, remote-controlled, line-laser measurement device that provides real-time graphic displays of both micro- and macrotexture (Cackler et al. 2006).

Results from research conducted to date indicate that for ordinary concrete pavements, longitudinal textures—including tining, grooving, and grinding—are particularly favorable in terms of low noise generation (Ardani and Outcalt 2005). Some of the quietest concrete pavements measured in North America are longitudinally-ground pavements, often called "whisper ground".

"Whisper grinding" refers to the practice of grinding concrete pavement specifically for improving its noise profile, as opposed to grinding for smoothness and ride. Blade width, blade spacing, and grinding depth are selected with noise mitigation in mind.

FHWA, in its recent Technical Advisory on Surface Texture for Asphalt and Concrete Pavements, includes longitudinal tining, grooving, and grinding as recommended practices to provide the desired texture over the performance life of the pavement and minimize objectionable levels of tire–pavement noise (FHWA 2005). Figure 11 depicts one of the quietest concrete pavement textures measured in North America (Section of I-94 along the MNRoad test facility).

Ongoing research is also looking at other innovative textures that may provide desired environmentally sensitive surface characteristics. Although experience with exposed aggregate textures is very favorable in Europe, in terms of both noise mitigation and cost effectiveness, there is very

Figure 11. Quiet, longitudinally grooved concrete pavement (photo courtesy of Diamond Surface, Inc.)

little experience and only a few installations with exposed aggregate textures in North America.

When ongoing research on optimal surface textures for noise is completed, public highway agencies and the paving industry will have even better guidelines for constructing concrete pavements that generate minimal noise at the tire–pavement interface, while still meeting or exceeding dry- and wet-weather friction requirements.

Another consideration when evaluating any pavement's performance in terms of noise is acoustic durability, or how tire–pavement noise changes over time as the pavement surface wears.

A pavement's noise profile must be considered not only immediately after construction but over the life of the pavement. Concrete pavements' inherently rigid structure reduces the potential for erosion of the desirable surface texture features under traffic loading. Unlike asphalt pavements, which are viscoelastic and therefore sensitive to both temperature and sustained or repetitive loading, concrete pavements much more readily retain their initial surface textures and the associated noise characteristics for the life of the pavement. As detailed in previous sections, this characteristic of concrete pavements also positively impacts both truck fuel economy and safety.

Conclusions

Concrete pavement has long been considered an environmentally and economically sustainable pavement choice for its longevity. This hallmark of concrete pavements ensures that the desirable performance characteristics of the pavement remain essentially intact for several decades. In addition, long-lasting concrete pavements do not require rehabilitation or reconstruction as often and, therefore, consume fewer raw materials over time. Energy savings also are realized, since rehabilitation and reconstruction efforts consume energy. Even more importantly, congestion is reduced by using long-lasting concrete pavements because of less frequent construction zones that impede traffic flow. Ultimately, all of these benefits add up to greater long-term economic and social benefits to the public.

However, there are many other features of concrete pavements that also support the case for concrete pavements' sustainability. As mentioned before, these features all contribute to making concrete pavements an environmentally sensitive pavement choice:

1. The rigidity of concrete pavement means lower vehicle fuel consumption and emissions.
2. Less fuel-intensive construction operations for concrete pavement result in enormous economic and CO_2 savings.
3. Using industrial byproducts in concrete improves pavement longevity, saves money, reduces the need for disposal in landfills, and greatly reduces both energy use and generation of greenhouse gases.
4. Concrete pavement's renewability and 100% recyclability lead to improved longevity and reduced demand on nonrenewable resources.
5. The strength and rigidity of concrete means fewer and thinner required layers of subbase materials.
6. The light-colored and cool surface of concrete pavement leads to improved visibility, reduced lighting requirement, and reduced heat island effects.
7. Concrete pavement's overall lower energy footprint means tremendous savings in energy over the life of the pavement facility.
8. Pervious concrete pavements capture and filter pavement runoff and help improve stormwater quality.
9. Optimized surface textures can be imparted on concrete pavements that result in long-lasting, quiet pavements.

These benefits result in greater long-term cost-effectiveness to the public. As such, concrete pavements are the clear choice for environmentally sensitive and economically sustainable roadways—truly green highways, in more ways than one.

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