Sustainable Asphalt Pavements: Technologies, Knowledge Gaps and Opportunities

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The purpose of this investigation is to increase awareness about gaps in technology regarding asphalt pavement sustainability. Presented here are *initial sustainability challenges* and available *methods, models and tools* that may be used to estimate pavement sustainability. Also presented are the *energy, emissions and environmental impact* of current and promising asphalt technologies as well as thoughts on *next steps for research* required in these areas.

Heat used in the production of hot mix asphalt (HMA) is one of the main targets in reducing its energy and environmental impact. Low-temperature mixes represent substantial energy savings and an associated mitigation of emissions. These mixes include cold mix asphalt (CMA), half-warm mix asphalt (HWMA) and warm mix asphalt (WMA). All show promise at reducing energy consumption, emissions and natural resource use, though more information is needed to draw definitive conclusions regarding use of these technologies from a pavement performance perspective. Recycled asphalt pavement (RAP) shows promise at reducing natural resource consumption and construction energy requirements. While reducing heat and increasing use of recycled asphalt are obvious techniques to make asphalt pavement more sustainable, the quantification of their benefits and impact on service life are unknown.

One opportunity for asphalt researchers is to continue developing and refining estimation tools so the industry can assess where it currently stands in key sustainability indicators and determine how much it can improve using low-energy and more recycled materials. Such estimation tools could allow the industry and road agencies to recognize the impacts of different sustainable construction techniques, materials and methods, as well as the potential cost and resource savings.

The Leadership in Energy and Environmental Design (LEED) program certifies environmentally friendly, low-impact materials and design methods for buildings. While a program like LEED does not currently exist for pavements, there have been discussions and efforts taken toward creating one. The creation of such a program may be attractive for the industry, users, and state and federal agencies.

INITIAL SUSTAINABILITY CHALLENGES

The initial challenges facing sustainability analyses of asphalt pavements are defining what a sustainable asphalt pavement is, collecting data that accurately reflect industry practices, and setting system boundaries for the sustainability analysis.

Challenge 1: Defining Sustainable Asphalt Pavements

The push toward low-energy, low-emissions and environmentally friendly construction methods is taking root in the asphalt industry, but it comes with the challenge of defining what "green" or "sustainable" actually mean in practice.

How might a green or sustainable asphalt pavement be defined? One definition, drawn from the United Nations' Brundtland Commission report, considers a sustainable pavement to be a safe, efficient and environmentally friendly pavement that meets today's transportation needs without jeopardizing the ability to meet such needs in the future (*1*). Another definition suggests an environmentally friendly road should minimize ground disturbance; be well-drained and appropriately surfaced to control erosion and loss of material; employ effective erosion control measures; and be regularly maintained while continuing to meet user needs (*2*).

For the purposes of this paper, a sustainable pavement may be defined as *a pavement that minimizes environmental impacts through the reduction of energy consumption, natural resources and associated emissions while meeting all performance conditions and standards.*

Challenge 2: Collecting Data

A second challenge lies in collecting data that accurately reflect industry practice. Industry surveys often provide information about contractor practices but then fail to capture proprietary methods and techniques that lead to competitive advantage within the industry. While common energy values and conversions are applied, variability exists even in well-established values. Developing surveys that are easily accessible to private contractors and road authorities would supplement the data currently available. Data related to energy consumption, resource consumption and plant efficiency would be necessary for accurate analyses of asphalt pavement sustainability.

Challenge 3: Setting System Boundaries

The third challenge lies in defining sustainable pavement system boundaries to establish what will and will not be included in the analysis. The availability of data influences the system boundaries that necessarily confine a pavement analysis. For purposes of this paper, the system boundaries will encompass five critical processes (as shown in Figure 1):

- Extraction of raw materials
- Manufacturing or production of paving products
- Construction or placement of materials
- Maintenance
- Removal, recycling or disposal

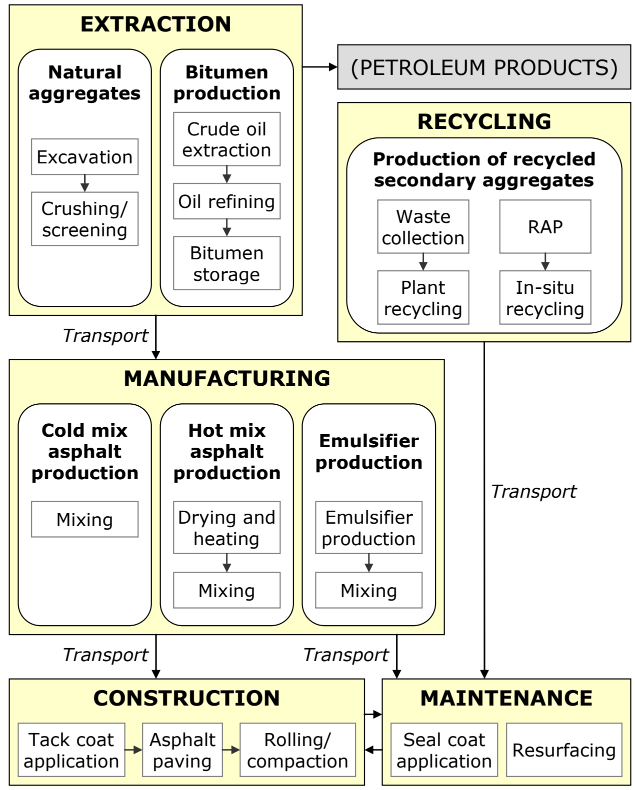

Figure 1. Five main processes comprise the system boundaries for the asphalt pavement life cycle analysis. This analysis excludes petroleum products.

Questions raised regarding pavement system boundaries include:

- Is earthmoving included?
- Is transportation of water or solvents on liquefied asphalts considered?
- Is manufacturing of the production plant hardware included?
- Is energy used to maintain the temperature of hot asphalt during storage and application considered?
- How is the production plant fueled and what is its operating efficiency?
- How are trucks modeled when carting raw materials?
- What is the pavement service life?

Setting system boundaries determines the resolution of the analysis. Figure 1 depicts the unit processes in asphalt pavement construction for the first three processes of raw material extraction, manufacturing of construction products and construction (*3*). As the amount of data collected increases, system boundaries may be expanded beyond the critical processes mentioned here. Defining system boundaries is critical in determining which factors are included in the analysis.

METHODS, MODELS AND TOOLS

Relevant methods, models and tools may be identified for estimating pavement sustainability indicators. Typical life cycle analysis (LCA) models capture lifetime costs but may neglect other important sustainability indicators such as energy consumption and emissions. A redefined LCA model with coherent system boundaries based on available data would include the following characteristics (*3*):

- Process parameters—data on transport distances, fuel efficiency and energy consumption in transport, materials production and construction
- Pavement processes—data on pavement dimensions, mix design and service life
- Unit inventory—inventory for unit operations of transport, materials production and construction
- Project inventory—aggregated data for unit processes of production, transport and construction
- Results—impact categories, including global warming potential, eco-toxicity, human toxicity and other sustainability indicators

Incorporating elements of this redefined LCA model may be useful in quantifying non-cost factors and benefits. One methodology, the eco-efficiency methodology developed by BASF, is an alternative LCA tool that suggests a framework for conducting sustainability analyses. The goal of this method is to quantify the sustainability of products and processes while ensuring short project times and low costs (*4*). The method output is the ecological fingerprint, which includes:

- Energy consumption
- Emissions
- Health effect potential
- Risk potential
- Resource consumption
- Land use

Values calculated from the ecological fingerprint are multiplied by weighting factors and normalized to obtain a graphical depiction that portrays each alternative as it relates to each of the six outputs (*5*). As shown in the example of the fingerprint (Figure 2), each of the six axes is independent, so an alternative that performs favorably in terms of risk potential might perform poorly in terms of energy consumption. Using the ecological fingerprint, optimizing the efficiency of the system is possible by identifying critical points where improvements can be made.

Several estimation tools have been developed to evaluate energy consumption per unit of material produced, hauled or constructed. Other models estimate emissions, benefits of using recycled materials and user costs (*6*). In addition to determining energy consumption, emissions and raw materials consumption, these tools can evaluate other environmental impacts and costs. Another promising tool was developed by the Waste Recycling Action Program (WRAP) (*7*). The WRAP tool synthesizes the best components of 26 sustainability and assessment models to promote the benefits of recycled secondary aggregates and carbon dioxide. Other analytical models based on spreadsheets are also available for obtaining estimates. Clearly the methods and tools for conducting life cycle assessments are not only applicable to the road industry, but are improving.

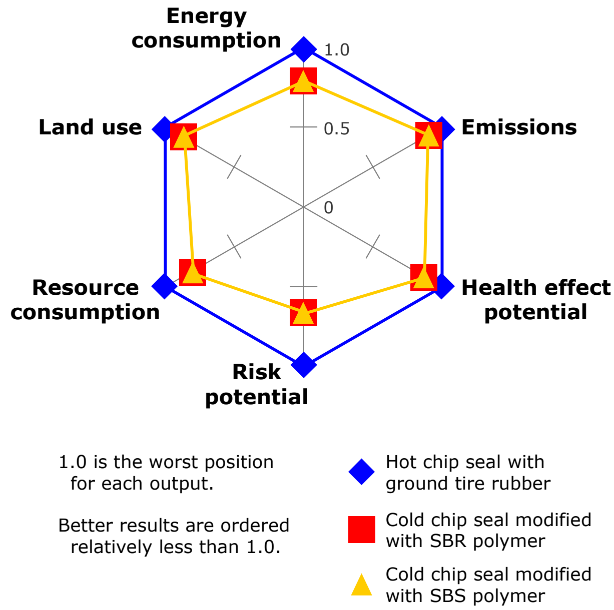

Figure 2. One modeling approach is BASF's eco-efficiency methodology, which generates an ecological fingerprint. Each axis compares a different ecological output for the alternatives. (Image adapted from BASF)

At this point, no single model or tool seems to be the desired "black box" that would allow the user to input given design values for any type of road and obtain a depiction of expected impacts and costs. Building on existing conventional models for life cycle assessments by incorporating WRAP tools into an eco-efficiency model could be a promising path forward.

A more comprehensive model would incorporate the six critical areas identified in the BASF eco-efficiency model while accounting for lifetime costs and pavement performance. Tools developed by WRAP and Land Transport New Zealand could be rendered to reflect the weighted importance of each factor, and provide DOTs and industry with a coherent estimation tool.

ENERGY, EMISSIONS AND ENVIRONMENTAL IMPACT

Envisioning a sustainable road may be easier than actually constructing it, but pathways to practically developing sustainable pavements lie in energy savings and natural resource conservation. Therefore, it is necessary to investigate the construction techniques, estimation methods and alternative technologies as they relate to these critical sustainability issues.

Several existing technologies have been introduced, all of which rely on the possibility of pavements being manufactured and constructed at lower temperatures. Constructing pavements using any one of these methods presents opportunities for energy savings and emissions reductions. But do these technologies actually save energy and reduce emissions? How much energy is conserved and how much are emissions reduced? Would these new types of pavements last as long?

Energy

Energy savings may be realized by reducing process temperatures for HMAs while developing warm, half-warm and cold mix techniques and pavement preservation strategies (*8*). Only recently has the cost of energy become a driving change in the road-building industry, and until now, little has been done to monitor energy use (*9*). Using low-temperature asphalt techniques can vastly reduce energy requirements, emissions and environmental impact. Given the five major processes within the system boundaries, each process may be considered in terms of energy consumption. Real data need to be collected and organized so that tools to calculate energy savings can be developed.

Extracting raw materials

The first process under consideration is the extraction of raw materials. Data are relatively constant across studies regarding fuel usage for the heavy machinery used to extract the materials. Relative to the other processes in the LCA, material extraction imposes minimal energy requirements. A push for recycling old aggregates rather than extracting virgin materials has emphasized the downstream process of recycling. RAP is being widely implemented in pavement projects. A need to quantify energy required for milling RAP and processing is necessary.

Manufacturing asphalt materials

Several studies confirm that the most energy-intensive process is the production of asphalt pavement materials, especially mixing and drying aggregates and producing HMA (*1*, *3*, *10*). Estimates suggest that nearly 50 percent of total production energy is required for mixing and drying aggregates; 40 percent of total production energy is required to produce bitumen (*10*).

Changes in aggregate storage and drying processes can substantially reduce energy consumption in asphalt pavement production. Producing low-temperature asphalts can vastly reduce the amount of energy required for these processes. Producing WMAs can reduce manufacture energy by as much as 15 percent, while HWMAs may lead to energy reductions on the order of 50 percent (*11*). Other studies estimate fuel savings of 11 percent to 35 percent for WMAs and up to 50 percent for low-energy asphalts such as CMAs or HWMAs (*12*). Energy conservation may be further increased with the use of foamed bitumen because aggregates need not be heated and can be mixed with the foam while cold or damp (*13*).

Figure 3. Asphalt production is the most energy-intensive process in the pavement life cycle. As a consequence, changes in production methods have the potential for the greatest energy savings. (Image courtesy of Rock Road Companies)

Another issue related to material manufacturing processes is plant efficiency. Some studies suggest targeting operating inefficiencies as a means of reducing energy consumption. Plant energy usage is controlled by several factors, including:

- Ambient temperature
- Aggregate moisture content
- Plant combustion efficiency

Regulating these variables may ensure that fuel use is optimized. Monitoring plant efficiencies can be achieved through careful placement of monitoring devices and technologies and regular maintenance of critical production equipment. A comprehensive list of operational measures and energy-saving guidelines is also available (*9*).

Constructing pavements

Pavement construction is a vital process in the analysis because it is the process resulting in direct user benefit and impact. The energy consumption of this process is minimal—about 1 percent of the total energy use of the cumulative traffic over the pavement lifetime (*1*). Modest reductions in vehicle energy consumption could easily offset the energy consumption in pavement construction processes.

Foamed asphalt is also considered beneficial because it may serve as a means of achieving base stabilization without significant energy use (*13*). Using low-temperature asphalts can also improve construction under suboptimal weather conditions, thereby prolonging the paving season (*12*). Compaction efforts may also be improved with improved workability. It is believed that using bitumen emulsions may be less expensive by roughly 15 percent compared to traditional HMA methods (*14*).

Maintaining pavements

Pavement maintenance is critical to preserving the integrity of surface layers while prolonging the service life. Maintenance is often considered the least energy-intensive process because it requires minimal improvements to the pavement structure and focuses on preserving the surface course. One low-energy maintenance method worth investigating is the use of CMA for patching and emulsion-based slurry seals. Advantages of these methods include a reduction in production energy and storage life. Using emulsion-based slurry seals with asphalts modified using recycled rubber is already widely used in parts of the United States. These maintenance methods deserve more research to quantify the savings in energy and conservation of new resources.

Removing and recycling pavements

The final process is pavement removal, recycling and disposal. Nearly 80 percent of all pavements are recycled, making asphalt pavement North America's most recycled construction product (*15*). One New Zealand study attempts to identify the primary reasons for the failure of the New Zealand road industry to adopt minimization strategies (*6*). The report concludes that waste minimization strategies, including recycling, are not widely employed because of a lack of experience on the part of the industry and little confidence in the use and performance of recycling technologies.

Figure 4. Asphalt is the most recycled construction product in the United States. The energy, emissions and environmental impact of recycling must be quantified. (Image courtesy of Asphalt Pavement Alliance)

In-situ recycling is widely regarded as the most energy-efficient recycling process. One study concludes that cold in-situ recycling with foamed bitumen consumes less energy compared with asphalt overlays or reconstruction (*16*). The data in the study suggest that cold in-situ recycling consumes 15 percent to 35 percent less energy than overlay projects, and 60 percent to 70 percent less energy than reconstruction projects. Cold in-situ recycling also allows for faster construction cycles than does reconstruction.

Full depth recycling (FDR) using foamed bitumen is also gaining popularity worldwide. The advantages of using FDR include:

- Lower life cycle costs
- Faster construction
- Reuse of aggregates (*17*)

Roads being considered for FDR often have multiple overlays, so the recycled material consists of cracked asphalt pavement. Recycling also offers countries lacking reliable pavement management systems the best alternative for structural rehabilitation (*16*).

Emissions

In addition to energy consumption, greenhouse gas (GHG) emissions are a critical issue for developing sustainable pavements. One Australian study concludes that ozone depletion is not a problem with emissions from bituminous binders (*18*). Other results from this study indicate heating of cutback and HMA releases GHG emissions because of the large amount of fossil fuels required and the evaporation of kerosene from cutback chip seals. Hydrocarbon evaporation may contribute to smog in urban areas, but is not a significant problem in rural areas. Contributions to air pollution from the volatilization of bituminous binder are small compared with emissions from energy production, transport and industrial processes.

Utilizing low-temperature asphalt technologies is widely regarded as a means to reduce emissions. As with energy consumption, the main process responsible for GHG emissions is the manufacture of pavement materials. An FHWA study of European practices concludes that expected reductions from using WMAs are:

- 30 percent to 40 percent for carbon dioxide and sulfur dioxide
- 50 percent for volatile organic compounds (VOCs)
- 10 percent to 30 percent for carbon monoxide
- 60 percent to 70 percent for nitrous oxides
- 20 percent to 25 percent for dust

Technologies that result in greater temperature reductions are expected to have greater emissions reductions (*12*). One estimate of a low-energy asphalt process results in a reduction of carbon dioxide emissions of about 9 kilograms per ton of aggregate. In the United States, this would translate into a reduction of about 5 million tons of carbon dioxide annually (*11*).

Another study finds that transporting emulsions results in greater fuel usage and related GHG emissions, but that this is insignificant compared to production and heating emissions (*19*). Furthermore, the study indicates that replacing cutbacks with emulsions would reduce the amount of carbon dioxide produced by almost two-thirds while reducing the production of photochemical, smog-generating VOC emissions.

Environmental Impact

Overall environmental impact can be considered in lieu of energy consumption and GHG emissions. Considerations such as water quality degradation, eco-toxicity and occupational health are important environmental factors.

In conducting an eco-efficiency life cycle assessment of chip seal alternatives, Wall compared the impacts of three chip seals (*5*). The analysis found that the cold chip seal alternative was advantageous in terms of risk potential, resource and energy consumption, health effect potential and land use compared to hot chip seal alternatives. These conclusions were based on the fact that the asphalt is applied at lower temperatures and uses fewer resources, energy and land because less asphalt is used in the chip seals. Additionally, the aggregate does not need to be precoated with asphalt. It was also found that not all recycling leads to reduced impacts: Although a ground tire rubber alternative diverted tires from landfills, this advantage was negated by higher emissions due to higher asphalt content and precoating of the aggregate as well as disadvantages in other environmental categories.

Emulsions are regarded by some as a safer alternative to HMA and cutback bitumen. In an Austroads study, researchers found that the benefits of using emulsions include worker health and safety compared to HMA or cutback because of lower handling temperatures and non-flammability (*18*). The study investigated evaporation of cutters, bitumen fume emissions, binder heating fuel use, binder transport use and general transport fuel use related to the road network. Researchers concluded that emulsions have a lower impact on the environment in terms of pollution and toxicity relative to cutbacks, especially in urban areas.

It was noted, however, that great care must be taken to avoid spilling emulsions into waterways. A New Zealand study concurs that emulsions are preferred as the environmentally beneficial method of sealing roads compared to cutback bitumen (*19*). A French study also considered emulsions the safest alternative due in part to reduced hydrocarbon volatility and heating temperatures (*1*).

Another study considered emulsions in terms of ecotoxicity (*20*). Findings from the study suggest that emulsions may be considered "slightly harmful" to the aquatic environment, while cutbacks may be considered "harmful." The study also found that the emulsifying agent was the only component of the emulsion that contributed to ecotoxicity. The report concluded that the major environmental danger of emulsions results from spillage and runoff, so great care must be taken to avoid overspray and tanker accidents. Slaughter's study confirmed that the water solubility of emulsions posed a greater risk to water contamination than cutbacks, and that cutbacks had not been reported to cause water pollution (*19*).

NEXT STEPS FOR RESEARCH

As the asphalt pavement industry continues to make strides in sustainable development, growing emphasis must be placed on energy consumption, emissions and environmental impact. A green road should be designed not only for long service life but for minimal energy consumption and environmental impact.

The authors, working for the University of Wisconsin Modified Asphalt Research Center (www.uwmarc.org), are mining published literature to raise awareness about opportunities in sustainable asphalt pavement development. Some of the promising ideas to move forward are:

Figure 5. MARC recommends next steps for achieving tomorrow's green asphalts.

- Refine and/or develop estimation tools to evaluate where the industry currently stands in key sustainability indicators. This base line could allow contractors and road agencies to recognize the potential cost and resource savings in using sustainable methods.
- Develop an initial certification program for asphalt road construction projects similar to LEED building certification. A point system could encourage industry to get involved and seriously consider alternative materials and methods for production and construction.
- Advance cold asphalt application specifications and test methods. While hot binder technologies have seen significant advances due to the Strategic Highway Research Program, emulsions and cold mixture technology have lagged behind. The science of asphalt emulsification should be the focus of significant research and development efforts.
- Quantify the effect of temperature on emissions and developing models that take into account asphalt chemistry, temperature, pressure and other climatic factors.

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