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Establishing a Framework for Analyzing Asphalt Pavement Sustainability

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Abstract: Much of America's civil infrastructure is in dire need of improvement. Electricity transmission grids, water distribution systems, bridges, and roads require modernization to restore functionality. Many studies support this need. The critical issue is how to meet this need of restoring and improving infrastructure while promoting an ethic of sustainability. Road construction and rehabilitation represent an often overlooked but important opportunity to implement energy-efficient technologies and techniques that reduce energy consumption, mitigate climate change impacts by reducing emissions, and promote sustainable resource consumption. We need a sustainable strategy to modernize our roads. Ongoing research at the University of Wisconsin-Madison is focused on identifying, testing, and validating alternative pavement technologies that may significantly diminish energy consumption through the reduction of material manufacturing and construction temperatures. Initial efforts have focused on developing quantitative lifecycle analysis tools for assessing pavement sustainability.

***Key words**: Asphalt pavement sustainability; Energy; Emissions; Environmental impacts; Green pavement; LEED; Sustainable.*

Introduction

This paper describes critical knowledge gaps to assess asphalt pavement sustainability. Understanding the implications of energy consumption and emissions are critical in determining overall social, financial, and environmental impacts of asphalt pavement technologies. Meeting these initial challenges is critical for establishing an analytical framework for assessing pavement sustainability. Initial challenges include:

1. Reaching consensus on what sustainability means for asphalt pavements.
2. Collecting and analyzing data that represent current pavement technologies and emerging technologies.
3. Defining system boundaries that are consistent among studies and robust enough to handle different locations, road types, and projects.

One opportunity for asphalt researchers, practitioners, and the industry is to continue developing and refining estimation tools and models that assess where existing technologies currently stand economically, socially, and environmentally. While several analytical tools do exist, insufficient data sets often limit full exploitation of analytical software. Understanding the shortcomings and deficiencies of existing tools is also important. Refining such estimation and modeling tools may allow asphalt producers, contractors, and road agencies to vigorously pursue alternatives to hot mix asphalt (HMA) while the industry and transportation sector define a Leadership in Energy and Environmental Design (LEED) analogue for certification of pavements.

Initial Challenges

The initial challenges are defining what a sustainable pavement is, collecting data that accurately reflect industry practice, and setting system boundaries for life cycle analyses. Success in meeting these challenges can lead to wider use and development of analytical estimation and modeling tools.

Challenge 1: Defining Pavement Sustainability

While the drive toward low energy, low emissions, and environmentally-friendly construction methods is taking root in the asphalt industry, it comes with the challenge of defining what *green* and sustainable actually mean in practice. Theoretically, sustainability is often described as the optimization of social, economic, and environmental dimensions, but what does this mean for asphalt pavements? Optimizing the use of natural resources, for example using reclaimed asphalt pavement (RAP), is the subject of many studies, but this practice alone does not constitute a sustainable pavement. What are the important characteristics of a sustainable pavement? What methods or metrics exist to quantify the sustainability of these characteristics? To a person more interested in getting to their destination safely and on time, the question may be: "Does a sustainable road look different than what I normally drive on?"

Determining a common language with which to discuss pavement sustainability is critical in utilizing relevant data and setting system boundaries. So how might a *green* or *sustainable* asphalt pavement be defined? One definition, based on the United Nations' Bruntland 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]. Other definitions employ similar rhetoric to convey the idea that a sustainable pavement should minimize overall environmental

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impact. Here, a sustainable pavement may be technically defined as a pavement that minimizes environmental impacts through the reduction of energy consumption, natural resources, and emissions while meeting all performance conditions and standards.

Challenge 2: Enhancing Data Collection

Beyond reaching consensus on a definition for sustainable pavements, a second challenge lies in collecting data that accurately reflect industry practice. Industry surveys and audits may provide information about contractors' practices but often fail to capture proprietary methods and techniques that lead to a competitive advantage within the industry. Investigating and refining survey tools to supplement existing equipment, materials, and performance data is needed. Developing surveys that are accessible to private contractors and road authorities provides a mechanism for contractors to inform the research that they may benefit from.

Operations data collected from manufacturing and raw material processing plants are needed to establish an industrial baseline for energy consumption and emissions. Plant production rates must be linked to coincident energy consumption rates, for a variety of fuel types, as well as emissions monitoring data and equipment operating efficiencies. While common energy values and conversions are widely known, variability exists even in well-established values. Benchmarking current production of HMA will provide useful input as warm mix asphalt (WMA) and cold mix asphalt (CMA) gain market share. Emulsified asphalt binders, a critical component in CMA, are not as widely used as HMA for structural applications because comprehensive specifications have not been instituted. It is difficult to justify a construction material that lacks comprehensive specifications, standards, and contractor confidence, even if the material is more sustainable.

Data related to energy consumption, resource consumption, and plant efficiency are necessary for conducting analyses on pavement sustainability. Just as pavement performance can be modeled using finite element methods, life cycle analysis methods necessitate a similarly rigorous and quantitative method for analysis that accounts for resource flows in and out of the system. While life cycle inventory and assessment methodologies provide a broad framework for analysis, such methods must be synthesized with performance data to fully capture the long-term implications of using selected materials, production methods, and construction techniques.

Challenge 3: Setting System Boundaries

A third challenge lies in defining system boundaries for the life cycle analysis. With a definition of pavement sustainability and sufficient data sets, the system boundaries define which information will and will not be included in the analysis. The availability of data influences the system boundaries: more data will enable more comprehensive analyses to be conducted, while less data will restrict the analysis to perhaps a single process in the overall life cycle. For purposes of this paper, the system boundaries will encompass five critical processes, as shown in Fig. 1. These processes include:

- Extraction of raw materials,
- Manufacturing or production of construction materials,
- Construction or placement of materials,
- Maintenance and rehabilitation of deteriorating layers, and
- Removal, recycling, or disposal.

A number of studies have investigated which of these five processes consumes the greatest amount of energy. It is generally believed that manufacturing asphalt concrete consumes more energy and emits more carbon dioxide and other noxious pollutants than other processes within the system boundaries. Additional data analysis is needed to validate this claim. Processes often excluded from the life cycle analysis include the extraction of raw materials, maintenance, and rehabilitation. Developing a consistent set of boundaries will enable data collected from studies on a single life cycle process to be integrated into a broader analysis.

Because no standard exists for defining system boundaries for asphalt pavements, questions frequently arise. Some questions include:

- Are all processes captured within the system boundaries?
- Does the analysis include the embodied energy of the construction materials?
- Is earthmoving included in the analysis? If so, how is it quantified, and by whom?
- Is transportation of water or solvents for emulsified asphalts considered?
- Is manufacturing of the production plant equipment included?
- Is the energy used to maintain the temperature of hot asphalt during storage and application considered?
- How is the production plant fuelled, and what is the plant operating efficiency? What does an optimized manufacturing plant look like, and what fuels are used?
- How are trucks modeled when carting raw materials? Is there an optimum cartage volume? What are the fuel efficiencies of transport vehicles?
- How many cycles of maintenance and rehabilitation are considered in the analysis?

Setting system boundaries determines the scope of the analysis. As the amount of data increases, system boundaries may be expanded beyond the processes mentioned here. Analyses often focus on a single process, such as manufacturing of construction materials or construction, while more sophisticated analyses may consider the entire cradle-to-grave life cycle. A cradle-to-cradle philosophy may also be appropriate for asphalt pavements, especially since asphalt pavement is widely considered to be the most recycled product in the United States. Practitioners need to speak a common language when conducting such analyses, and this must be apparent in selection of the system boundaries. Despite a growing understanding of low energy mix performance, synthesis of trial studies is often limited and relies on different assumptions, system boundaries, and analysis tools in drawing conclusions.

Estimation Models and Tools

With definitions of pavement sustainability, adequate data sets and well-defined system boundaries in place, estimation models and tools can assist in processing the information. Typical life cycle analysis models capture lifetime costs but may neglect other important

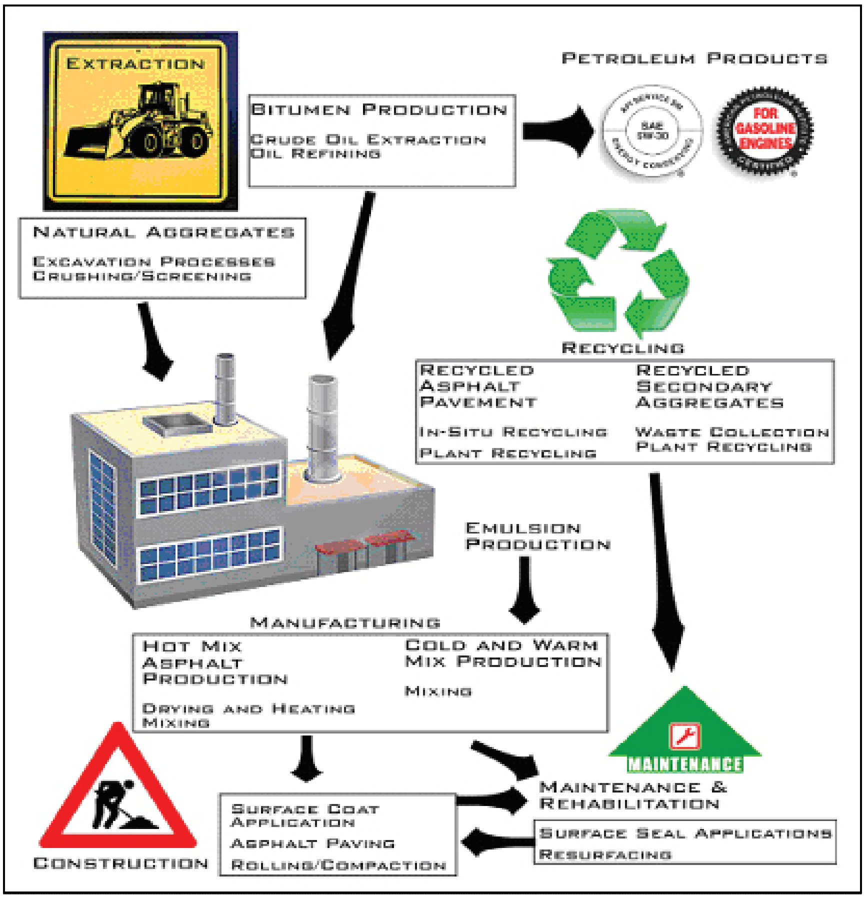

Fig. 1. Typical System Boundaries for Asphalt Pavement Life Cycle Analysis.

sustainability indicators such as energy consumption and emissions. A redefined life cycle analysis 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 life cycle model may be useful in quantifying non-cost factors and benefits. One methodology, the eco-efficiency methodology developed by BASF, is an alternative life cycle analysis 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, and
- 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, as shown in Fig. 2. Each of the six axes is independent, so an alternative that performs favorably in terms of risk potential may perform poorly in terms of energy consumption [5]. Using the ecological fingerprint or similar graphical depictions, optimizing the efficiency of the system is possible by identifying critical points where improvements can be made.

Several estimation tools have been developed to estimate 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 energy consumption, emissions, and use of raw materials, other environmental impacts and costs can be evaluated using these tools. The Waste Recycling Action Program (WRAP) developed a promising tool that synthesizes the best components of 26 sustainability and assessment models to promote the benefits of recycled secondary aggregates with respect to carbon dioxide emissions [7]. The PaLATE spreadsheet model is structured similarly to the WRAP model and may be more user-friendly, though it lacks the capability to analyze the use and operation phases of the pavement life cycle. The U.S. Environmental Protection Agency's Mobile 6 tool exists for analyzing emissions generated in the use phase.

Aside from spreadsheet analysis tools, the Greenroads program

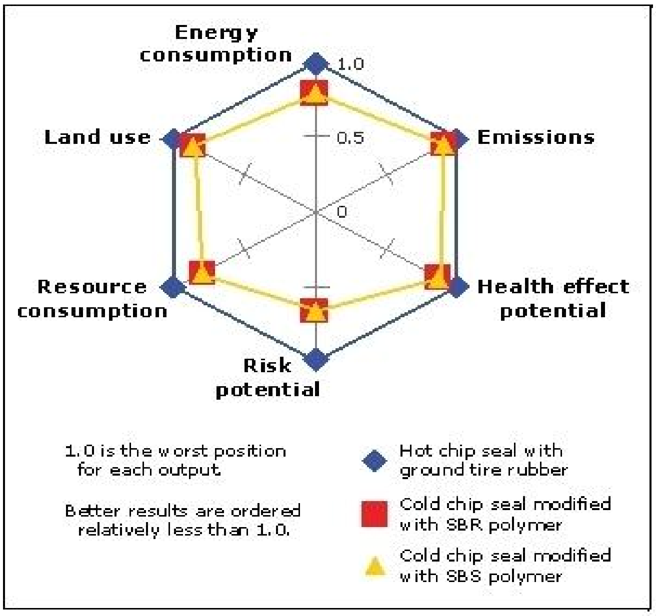

Fig. 2. One Modeling Approach is BASF's Eco-Efficiency Methodology, which Generates an Ecological Fingerprint; Each Axis Compares a Different Ecological Output for the Alternatives. (Adapted from BASF.)

is an analogue to the LEED rating system for buildings and structures. Greenroads is a rating system developed by the University of Washington and CH2M Hill that distinguishes sustainable pavement projects and focuses on the design and construction phases. Greenroads places less focus on the mechanics or performance of particular asphalt mixtures and more emphasis on the overall, holistic impacts of particular road projects. Though not mandated, Greenroads proposes seven primary categories that earn points toward four levels of certification. These categories include:

- Minimum project requirements,
- Environment and water,
- Access and equity,
- Construction activity,
- Materials and resources,
- Pavement technology, and
- Exemplary performance.

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. Models must be robust enough to incorporate lab data related to emissions as well as field data collected at project sites and data supplied by contractors and road controlling authorities. These data are critical for validating estimated values and confirming assumptions. A comprehensive model would incorporate the six critical areas identified in the BASF eco-efficiency model or the seven areas identified in the Greenroads program while accounting for lifetime costs, overall environmental impact, and pavement performance. The WRAP, PaLATE, and Land Transport New Zealand models or similar models could be refined to reflect the weighted importance of each factor and provide road authorities and industry practitioners with a coherent estimation tool that further informs public policy.

Assessing Energy, Emissions, and Environmental Impact

Envisioning a sustainable road may be easier than actually constructing it, but pathways to developing sustainable pavements lie in energy savings, emissions mitigation, and natural resource conservation. Several low-energy technologies have been introduced by various contractors and labs, all of which focus on the opportunities of manufacturing and constructing pavements at lower temperatures. Constructing pavements using these materials presents opportunities for energy savings and emissions reductions to varying degrees. But how much energy is conserved and how much are emissions reduced? Will these paving materials last as long? Sustainable pavements must optimize resource conservation, carbon emissions, and energy consumption, as shown in Fig. 3.

Energy

Energy savings may be realized by reducing process temperatures for hot mix asphalts 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 industry, and until now little has been done to monitor energy use [9]. Utilizing low-temperature asphalt techniques can vastly reduce energy requirements, emissions, and environmental impacts. Five processes identified as critical to the life cycle analysis are considered here.

Compared to other processes in the pavement life cycle, material extraction imposes minimal energy requirements so long as the extraction and production of bitumen is excluded. Data are relatively constant across studies regarding fuel usage for heavy machinery used to extract raw materials, especially aggregates. A push for recycling of old aggregates rather than extraction of virgin materials has emphasized downstream recycling processes. RAP is widely utilized in pavement projects, and incorporation of RAP into standard mixes is often required by road authorities. There is a need to quantify the energy required to mill and process RAP.

Several studies suggest that the most energy intensive process is the production of asphalt pavement materials, especially mixing and drying of aggregates and production of HMA [1, 3, 10]. Estimates suggest that nearly 50 percent of total production energy is required for mixing and drying of aggregates; 40 percent of total production energy is required to produce bitumen [10]. Changes in storage of aggregates and drying processes can substantially reduce energy consumption, and producing low-temperature asphalts can vastly reduce the amount of energy required for these processes. Producing WMA can reduce manufacture energy by as much as 15 percent, while half-warm mix asphalt (HWMA) may lead to energy reductions on the order of 50 percent [11]. Other studies estimate fuel savings of 11 to 35 percent for WMA and up to 50 percent for low-energy asphalts such as CMA or HWMA [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].

Another issue related to energy consumption in manufacturing processes is plant efficiency. Some studies suggest targeting operating inefficiencies to reduce energy consumption. Plant energy

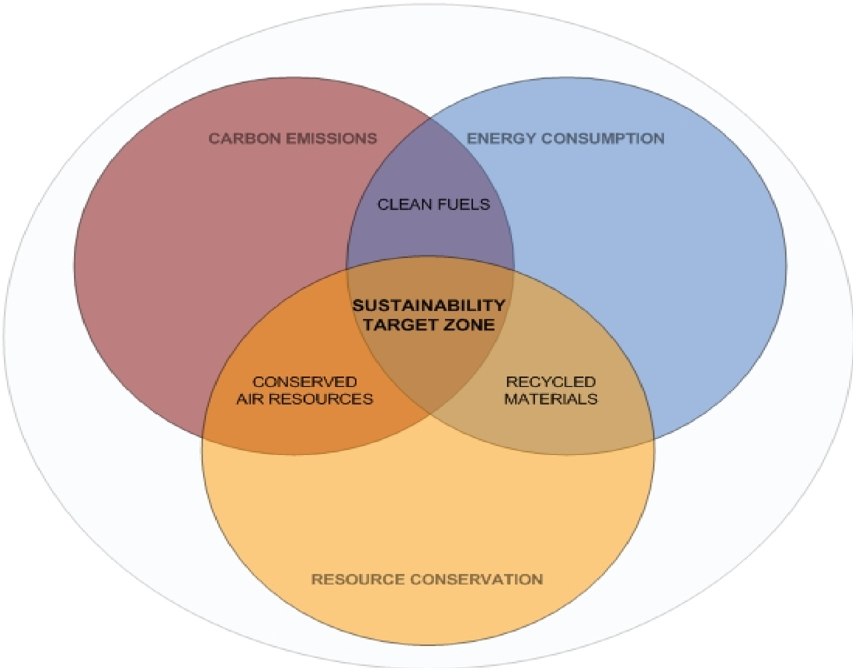

Fig. 3. Sustainable Pavements Must Optimize Resource Conservation, Energy Consumption, and Carbon Emissions.

usage is controlled by several factors, including ambient temperature, aggregate moisture content, and plant combustion efficiency. Regulating these conditions 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].

Pavement construction is a critical process that results in direct user benefit and impact. The energy consumption of this process is minimal compared to the total energy use of cumulative traffic over the pavement lifetime [1]. Foamed asphalt is considered beneficial because it may serve as means of achieving base stabilization without significant energy use [13]. Using low-temperature asphalts can also improve construction under sub-optimal weather conditions and prolong the paving season [12]. Compaction efforts may also be improved with improved workability. It is believed using bitumen emulsions may be less expensive by roughly 15 percent compared to traditional HMA methods [14].

Pavement maintenance is critical to preserving the integrity of surface layers and prolonging the pavement 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. CMA is often considered for patching and emulsion-based slurry seal applications. Advantages of these methods include 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 resources.

The final process in the pavement life cycle is removal, recycling, or disposal. Nearly 80 percent of all pavements are recycled in the United States, 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 due to a lack of experience on the part of industry and little confidence in the use and performance of recycling technologies.

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 to asphalt overlays or reconstruction [16]. The data in the study suggest that cold in-situ recycling consumes 15 to 35 percent less energy than overlay projects and 60 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. Roads being considered for FDR often consist of multiple overlays. Recycling also offers countries lacking reliable pavement management systems the best alternative for structural rehabilitation [16].

Emissions

The global origin and impact of climate change demands a global response. Because roads are ubiquitous, cost savings as well as energy and emissions savings can be realized anywhere a road is constructed. Nearly limitless opportunities exist for scaling up proven, energy-efficient pavement methods and technologies. A growing body of technical and engineering knowledge suggests that reducing energy consumption and emissions is essential in the quest to ameliorate the increasing impacts of climate change. The important question from the climate change perspective is: How can roads be developed and constructed at scale to mitigate a considerable wedge of carbon dioxide emissions, on the order of gigatonnes ($10^{12}kg$), in the next 10 to 20 years?

The prospect of mitigating carbon dioxide emissions is technically and economically feasible and environmentally imperative. Soon the mitigation of emissions may be politically imperative as well, with tightening emissions regulations and a cap-and-trade program looming. The asphalt pavement industry must position itself now to stay within emissions limits to remain economically moving forward. One study concludes that ozone depletion is not a problem with emissions from bituminous binders [17]. Other results indicate heating of cutback and HMA releases green house gases (GHGs) due to the large amount of fossil fuels required and the evaporation of kerosene from cutback chip seals. Evaporation of hydrocarbons may contribute to smog in urban areas, but it is not a significant problem in rural areas. Contributions to air pollution from the volatilization of bituminous binder are small compared to 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 GHGs is manufacture of pavement materials. A Federal Highway Administration study of European practice concludes that expected reductions from using WMA are [12]:

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

Technologies that result in greater temperature reductions are expected to have greater emission reductions [12]. One estimate of a low energy asphalt process reported a reduction of carbon dioxide emissions of about 9*kg* 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 GHGs, but that this is insignificant compared to production and heating emissions [18]. The study also indicates that replacing cutbacks with emulsions would reduce the amount of carbon dioxide produced by almost two-thirds while reducing the production of photochemical volatile organic compounds.

Environmental Impact

In addition to energy consumption and emissions, water quality degradation, eco-toxicity, and occupational health are other factors that must be considered in transitioning from HMA to low energy asphalt pavements. These factors may be taken into account in an environmental impact assessment, but are typically not considered in the design of the road itself. Emulsions are widely regarded as a safer alternative to HMA and cutback asphalts for a number of reasons.

In conducting an eco-efficiency lifecycle 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 (refer to Fig. 2). 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. Aggregates do not need to be pre-coated 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 pre-coating of the aggregate as well as disadvantages in other environmental categories.

In an Australian study, researchers found that the benefits of using emulsions include worker health and safety compared to HMA or cutback due to lower handling temperatures and non-flammability [17]. 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. The conclusion was that emulsions have a lower impact on the environment in terms of pollution and toxicity compared to cutbacks, especially in urban areas.

Emulsions can also be considered in terms of eco-toxicity [19]. Findings from a New Zealand study suggest that emulsions may be considered “slightly harmful” to aquatic environments, while cutbacks may be considered “harmful”. The study found that only the emulsifying agent contributed significantly to eco-toxicity due to the water-soluble nature of emulsions. Major environmental dangers result from spillage and runoff, so great care must be taken to avoid spilling emulsions into waterways. A second New Zealand study concurs that emulsions are preferred compared to cutback bitumen [18]. A French study also considered emulsions the safest alternative due in part to reduced hydrocarbon volatility and heating temperatures [1].

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–Madison’s Modified Asphalt Research Center (www.uwmarc.org), are mining published literature to raise awareness about opportunities in sustainable asphalt pavement development. Some promising ideas to move forward are to:

- Conduct energy and emissions analyses at local asphalt manufacturing plants. Survey tools and audit forms exist and should be used whenever possible to collect data.
- Refine and develop estimation tools to evaluate where the industry stands in key sustainability indicators. Building on existing conventional models for life cycle assessments by incorporating spreadsheet tools into an eco-efficiency model or the Greenroads program could be a promising path forward.
- Develop an initial certification program for asphalt pavements 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, 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 develop models that account for asphalt chemistry, temperature, pressure, and other climatic factors.
- Construct and manage a comprehensive, open source database to enable approved contributors to add pertinent project or contractor data that could be synthesized into broader analysis models.

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