

Environmental Impacts of Producing Asphalt Mixtures with Varying Degrees of Recycled Asphalt Materials

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ABSTRACT

The environmental impacts of producing asphalt mixtures with different percentages of asphalt binder replacement (ABR) are assessed using the technique of life cycle assessment (LCA). In this paper, only the material production phase of the pavement life cycle is considered. To improve the quality of the LCA, a regionalized life cycle inventory (LCI) database for the Northern Illinois region is compiled for the production of various materials used in flexible pavement construction. Data from local questionnaires, published literature, and commercial LCI databases are used to validate and model unit processes with a LCA software. The environmental impacts modeled include energy consumption and greenhouse gas (GHG) emissions from producing asphalt binder, recycled asphalt materials, and aggregates as well as from operating hot-mix asphalt plants. Using the regionalized LCI database, a partial LCA is used to investigate the environmental effects of producing asphalt mixtures with increasing ABR contents. Eleven mixes containing varying percentages of recycled asphalt pavement and recycled asphalt shingles are analyzed. When compared to a mix with 0% ABR content, 25% ABR mixes show an average decrease of 6.3% in energy and 6.5% in GHGs while a 60% ABR mix shows savings of 20.9% and 21.8%, respectively. In addition, conducting the same case study using asphalt binder LCI data from different sources reveals differences of up to 135 GJ and 9.9 tonnes of CO₂e per 3-inch-lane-mile in environmental savings for using the 60% ABR mix, emphasizing the importance of using the most relevant LCI data when performing environmental analyses.

INTRODUCTION

The roadway is essential for a nation's economic strength and mobility. The construction of roadway infrastructure is an energy and resource-intensive process, releasing a large amount of emissions to the environment and resulting in the depletion of natural resources. Recognizing the need to strive toward sustainability, the U.S. national pavement industry has implemented design practices to reduce emissions and energy consumption. The environmental burden of pavements may be reduced through the implementation of new strategies. One of these strategies, life cycle assessment (LCA), has been receiving considerable attention from the industry for its ability to systematically and holistically assess the environmental performance of pavement throughout its life cycle.

The life cycle stages of any product typically involve five stages: production, construction, use, maintenance, and end of life (EOL). In this paper, the first stage, material production, will be considered for pavements. The case study included in this work focuses on asphalt mixtures used in flexible pavements and specifically mixtures containing recycled asphalt materials. The paper begins with a literature review of current LCA frameworks that have been implemented, focusing on existing studies that address recycled materials. The subsequent sections of the paper describe the LCA framework, as directed by the International Organization for Standardization (ISO) 14044:2006 requirements and regulations for environmental management and LCA. A definition of the goal and scope of the study is given, followed by a description of the regionalized life cycle inventory (LCI) database and the impact assessment methods that are considered. Finally, a case study of asphaltic mixes containing varying amounts of recycled asphalt material will be presented and analyzed using the aforementioned LCA framework.

LITERATURE REVIEW

There are several approaches for conducting LCA, two of which are the process-based LCA and the hybrid LCA. The process-based LCA identifies and quantifies the inputs and outputs of individual processes that occur during the life cycle of a product at any stage. The hybrid LCA applies an economic input-output analysis with the information relevant to national gross domestic product for upstream processes and a process-based LCA for downstream processes. The process-based LCA typically provides more accurate and nuanced results; however, this type of LCA is considered more resource-intensive than the hybrid approach. Some of the LCA studies that have assessed the environmental burden of different types of pavement were conducted using a process-based LCA (1–3), while others used a hybrid LCA (4–5).

Even if the same LCA approach is used, the results from different studies could differ significantly. For example, studies using the process-based approach by Stripple (2) and the Athena Institute (3) compared flexible and rigid pavements in terms of energy consumption and greenhouse gas (GHG) emissions or global warming potential (GWP). Stripple showed that the energy and GHG emissions for rigid pavements in Sweden were 30% and 29% higher, respectively, than that for flexible pavements when material, construction, and maintenance phases were considered. On the other hand, the Athena Institute showed that the energy use and GHG emissions for flexible pavements in Canada were 40% and 6.8% higher, respectively, than that for rigid pavements when material, construction, and maintenance phases were considered. Many factors influence the results of LCA and are likely to explain the discrepancies observed. These factors may include system boundaries, inventory data validity and quality, geography, traffic, analysis period (e.g. 40 years for Stripple and 50 years for the Athena Institute), and the assumed long term performance of pavements.

There are a limited number of LCA studies regarding the importance of recycled materials in the pavement industry. Recycled materials are widely used for reducing environmental burdens. Examples of such materials in pavement industry include reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), steel slag, fly ash, and granulated ground blast furnace slag (GGBFS). Asphalt concrete covers more than 90% of the nation's paved highways and roads, and RAP is an abundant recycled material with nearly 45 million tons produced every year in the U.S (6). The use of RAP has been regarded as a sustainable construction practice in the pavement industry because RAP is a good alternative to virgin aggregate in hot-mix asphalt (HMA) production and in the construction of base/subbase courses. RAS is another recycled material produced from used asphalt roofing shingles or manufacturing waste. Approximately 0.75–1.0 million tons of manufactured shingle scraps are generated annually in the U.S. With such great recycling potential, RAS can be considered a sustainable alternative due to its economic competitiveness, reduced burden on landfills, and replacement of virgin materials (aggregate and binder) in asphalt mixes (7).

Several studies have investigated the impact of using RAP in pavement. The Athena Institute found that the reduction in energy and GWP from using 20% RAP in asphalt mixes was approximately 7.5% and 13%, respectively, for Canadian arterial highways considering a 50-year life cycle (3). Another study by Santistevé et al. reported that the use of 15% RAP versus 0% RAP in HMA brought a 13–14% decrease in all endpoint impacts in addition to climate change, fossil depletion, and total cumulative energy demand over the pavement's life cycle (8). Case studies conducted by Huang et al. reported that the use of 25% RAP and 10% incinerator bottom ash in asphalt pavement contributed a 4% reduction in both total energy and CO₂ in material production and construction (9). Another study by Aurangzeb et al. found that 30%, 40%, and 50% RAP replacements decreased total energy and CO₂ by 7.3%, 9.8%, and 12.2%, respectively, as compared with the case where RAP was not used for material production and construction (10). Finally, a recent study by the U.S. Environmental Protection Agency (U.S. EPA) reported that using 20% RAP and 7% RAS in an asphalt mixture reduced GHG emissions by 16% with no landfill credit, emphasizing the importance of recycled asphalt materials in material production (7). The degree of savings in total energy use and GHG emissions differs from one project to another as each study is based on different assumptions, system boundaries, and geography. However, these studies in the literature have consistently shown that the use of recycled materials such as RAP may bring environmental benefits to roadway construction so long as pavement performance is not compromised.

DEFINITION OF GOAL AND SCOPE

Goal and Scope

This paper investigates potential savings in energy consumption and GHG emissions in the material production phase of flexible pavements based on different asphalt binder replacement (ABR) rates obtained using various amounts of RAP and RAS in asphalt mixes. The paper includes a case study comparing various ABR mix designs used in Illinois. The results demonstrated in this paper are based on a regionalized LCI database developed for the Northern Illinois region. The case study is only limited to the material phase of the pavement life cycle, attempting to observe the initial impact of using recycled materials. The results in the case study were computed using a pavement LCA tool developed by the University of Illinois at Urbana-Champaign in collaboration with Applied Research Associates, Inc. (ARA), and theRightEnvironment for the Illinois State Toll Highway Authority (Illinois Tollway). A different case study investigating the material production and construction phase of pavements taking into account traffic delay was performed using an earlier version of this tool with an inventory

database that was not compiled in SimaPro (20). The target audience of this LCA study consists of governmental organizations, academic researchers, engineering consulting firms, and pavement material manufacturers interested in environmental issues related to pavements.

Functional Unit

The functional unit is a reference unit to which the input and output data are normalized. In this study, the functional unit is one lane-mile of pavement from a roadway intended to perform sufficiently in Illinois.

System Boundaries

The system boundaries define which unit processes are included in the LCA study. The ISO 14044:2006 guidelines emphasize that system boundaries should be consistent with the goal of the study (16). The processes included in this LCA are related to the material production phase of the pavement life cycle, so they include the production of mix materials as well as HMA plant operations. The remaining life cycle phases are not considered, so the environmental impacts do not take into consideration the construction, maintenance, and performance of the mixes. Further work must be done to evaluate the other phases, especially the use phase, which will govern the service life and thus affect the environmental impact expected. For example, Aurangzeb et al. (10) studied the effect of pavement performance on the environmental performance of RAP mixtures by defining breakeven performance thresholds. These thresholds indicated the levels of pavement performance at which the environmental benefits of the recycled mixtures would be henceforth offset by the environmental burdens resulting from additional maintenance activities.

The energy and emissions associated with upstream and downstream processes are considered. In other words, the energy and emissions needed to produce primary and secondary energy sources such as fossil fuels and electricity, as well as those resulting from downstream processes, such as direct combustion of fossil fuel in manufacturing pavement materials, are considered using US-Ecoinvent 2.2 (US-EI 2.2) (21), Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) (12) by Argonne National Laboratory, and the Emission and Generation Resource Integrated Database (eGRID) (13) by the U.S. EPA.

LIFE CYCLE INVENTORY ANALYSIS

The study focuses specifically on Illinois roadways, so it is important to develop a regional inventory database to reflect the site context. Thus, in order to improve the appropriateness of the inventory database, reliance on generic literature sources is avoided. Confidential LCI questionnaires were distributed in 2012–2013 to local material suppliers and plants in Northern Illinois for regional data collection.

Questionnaire responses were received for many pavement materials: HMA, RAP, Portland cement, aggregate, ready-mix concrete, and GGBFS. A detailed description of the preliminary data collection and interpretation of the results are discussed elsewhere (14). However, the responses received via questionnaires are not enough to develop a complete regionalized LCI database. Therefore, SimaPro, a commercial LCA software, is used to model various unit processes using collected and published data sources.

Collected questionnaire responses are initially analyzed and compared with the literature and US-EI 2.2, a commercial LCI database. Pre-screened questionnaire data are then used to model and develop a regionalized database in SimaPro. After unit processes are modeled in SimaPro, the results are benchmarked with similar processes from US-EI 2.2 and literature values for validation. The major unit processes used in the production of asphalt mixtures are described in the following subsections.

Electricity and Fuels

Developing regional electricity and fuel models is an important step in regionalizing the LCI database, as large amounts of electricity and fuels are consumed in the material production phase. The regional electricity model used in this study considers the production and transmission of electricity in Illinois. Regional fuel mixes, plant efficiencies, and major emissions associated with electricity generation in Illinois are calculated using eGRID and then modeled in SimaPro.

Regional fuel models can consider the production and transportation of coal and natural gas used in Illinois. The U.S. national fuel mixes and fuel combustion processes to produce coal and natural gas are calculated based on GREET. The distances and modes of transportation from various sources to Illinois are also calculated based on data provided by the U.S. Energy Information Administration (EIA) (22–23). Appropriate combustion processes are selected in US-EI 2.2 and the regional coal and natural gas models are generated in SimaPro. For the case study in this paper, the inventory database considers only the regional electricity model, as the regional coal and natural gas models have yet to be implemented in the database.

Asphalt Binder

In flexible pavements, the production of asphalt binder incurs the greatest environmental impact out of all the raw materials in the material production stage. Current life cycle inventories for binder production are often limited to studies by Athena Institute (17), Eurobitume (18), Häkkinen and Mäkelä (1), and Stripple (2), which were obtained using region-specific data from U.S./Canada, Europe, Finland, and Sweden, respectively. However, it has been found that the range of environment impacts from manufacturing petroleum products are highly susceptible to regional factors, especially crude oil sources (19). Thus, a LCI model for asphalt binder is developed in this study to represent binder production in the U.S. Midwest, where Illinois is located.

A preliminary version of this model using only open source data (i.e. without US-EI 2.2) is described elsewhere (20). The system boundaries for the preliminary model included crude oil extraction, flaring, and transportation as well as refining, refined transportation, and blending terminal storage. Information from EIA was used to determine the location and percent distribution of crude oil sources as well as the fuel input and market value allocation for refining. A similar approach is used in this study; data has been updated to include averaged values from 2005-2012 for the Petroleum Administration for Defense District II (PADD2), corresponding to the Midwest region. Most significantly, the previous model used energy consumption and emissions from GREET for crude extraction and refining operations. In this updated study, appropriate crude extraction processes pertaining to different world regions (North America, Middle East, Africa, and Nigeria) from US-EI 2.2 are used to model crude extraction. In addition, corresponding fuel combustion processes from US-EI 2.2 are used to model fuel input for refinery operations, and other appropriate transportation and operations processes are likewise modeled in SimaPro.

In addition to process energy, feedstock energy is also another consideration in binder production. ISO 14044:2006 defines feedstock energy as the “heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value” (16). The inclusion of feedstock energy for asphalt binder is highly contested because it is not commonly used as a fuel in any applications. However, ISO recommends that feedstock energy be included, so in this study, the feedstock from the binder is considered to be 40.2 MJ/kg or 3,647 MJ/ton and will be reported separately in the case study to observe its effect.

Figure 1 shows a comparison of the energy consumption and GHG emissions for asphalt binder production from published sources to the model developed in this paper by the Illinois Center for Transportation (ICT). These other sources include binder production by Stripple for Sweden (2), Eurobitume for Europe (18), Athena Institute for U.S./Canada (17), Häkkinen and Mäkelä for Finland (1), and US-EI 2.2 for Europe adjusted for U.S. electricity (21). The energy consumption and GHGs for the ICT model fall in the middle range of the reported external models. Various reasons justify the observed discrepancies, aside from inherent regional differences in fuel use and processes. The system boundaries of the models are not all the same – Athena and Häkkinen and Mäkelä do not include refined transportation or blending storage, while Eurobitume does not include refined transportation. In addition, Eurobitume and ICT use economic-based allocation in refining, while Stripple, Athena, and US-EI 2.2 use mass-based allocation. Thus, it is important to acknowledge the system boundaries for the process and to understand that significant differences may emerge when comparing regionalized LCI data.

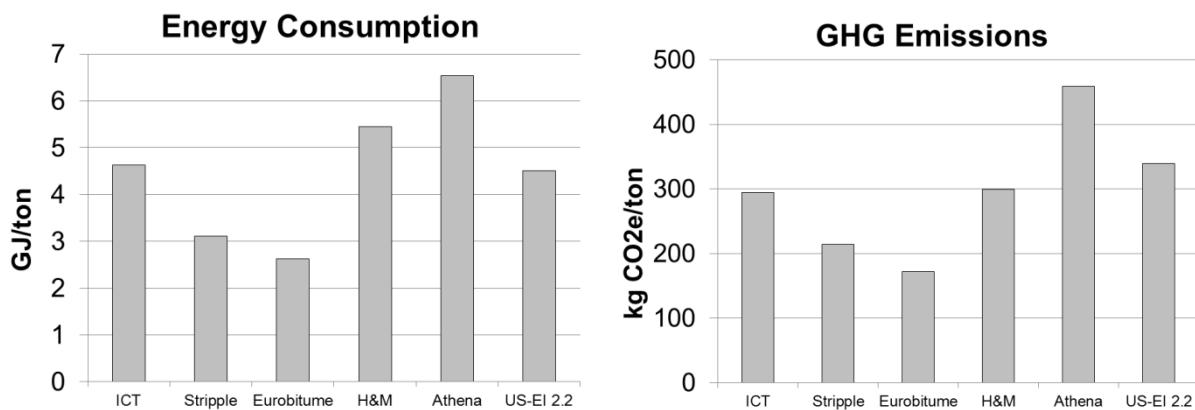


Figure 1: Comparison of various sources of asphalt binder (L) energy consumption and (R) GHG emissions.

Recycled Asphalt Materials

In this study, a cut-off approach is used to account for the burdens and benefits of recycled materials (24–25). Therefore, the environmental impacts associated with producing the original material will be fully attributed to the original material and none to the recycled materials. The production of RAP starts with plant processing, such as crushing and screening, but the burdens of milling and transporting demolished pavements to recycling facilities are attributed to the EOL of the previous pavement. Based on a survey response, the production of RAP is modeled in SimaPro and includes the operation of multiple loaders for in-plant transportation

and the crushing machine. Appropriate combustion processes are selected from US-EI 2.2 to model emissions from various plant equipment based on fuel and equipment types.

The production of RAS excludes excavation and removal because they are considered part of the EOL activities of asphalt roofing shingles. The relevant processes in RAS production include grinding and removing metal pieces. However, the energy values reported in the questionnaire were too high compared with the values reported in literature, so the environmental impacts of RAP are assumed to be the same for RAS.

In addition, both types of recycled asphalt materials are considered to be free of any feedstock energy, even though they arguably retain a portion of their feedstock energy over time. It is unknown what portion of this feedstock is retained and how the feedstock energy should be allocated between virgin and recycled asphaltic materials. Non-trivial processes may be needed to clean and extract the asphalt to use it as a fuel, affecting the potential energy available. Also, if feedstock is considered for RAP and RAS, preemptive allocations must be made for any virgin binder used to avoid double-counting. Due to these uncertainties the feedstock retained in RAP and RAS will not be considered, underestimating the total embodied energy in these materials where feedstock is considered.

Aggregates

In this study, aggregates are classified into two categories: natural and crushed. A default aggregate production process in the US-EI 2.2 database is used for natural aggregate whose system boundary includes dredging, land use, and internal transportation and processes. Similarly, crushed aggregate is based on a default US-EI 2.2 process whose system boundary includes limestone mining, primary/secondary/tertiary crushing, screening and washing, and transportation by conveyor belt.

Hot-Mix Asphalt Plant

The production of asphalt mixes entails considerable energy consumption and GHG emissions in preparation for pavement construction. In Illinois, the majority of asphalt mix plants are drum-type and use natural gas as the primary energy source for energy intensive operations such as aggregate drying and mixing. The system boundary considered for asphalt mix plants includes raw material transportation, in-plant transportation, plant operations, and truck loading. Information about the fuel and electricity used in plant operations and in-plant transportation is taken from questionnaire responses. Average hauling distances are assigned for raw material transportation to the plant site. The inclusion of fugitive emissions (15) from load-out, asphalt storage, and loaded trucks do not affect the environmental impacts considered in this paper; therefore, fugitive emissions are not considered at this point.

IMPACT ASSESSMENT

Per the steps prescribed in ISO 14044:2006 for conducting LCA, impact assessment must be performed after inventory analysis (16). The metrics chosen for this study include GHGs and energy consumption. GHGs or global warming potential (GWP) is calculated using the characterization given by the U.S. EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI v2.1) (26). Cumulative energy demand is used to calculate the total energy consumed by each process. Table 1 summarizes the energy consumption and GHGs of the materials and processes considered in this study.

Table 1: Summary of Impacts and Sources for Flexible Pavement Processes

Process	Energy (MJ/short ton)	GWP (kg CO ₂ e/short ton)	Data Source
Asphalt binder production	4633	294	Regional model
RAP and RAS production	17.4	1.3	Local survey
Coarse aggregate production	29.8	2.1	US-EI 2.2
Natural aggregate production	51.0	3.2	US-EI 2.2
HMA plant operations	400.4	23.8	Local survey

CASE STUDY

Using the LCI database developed in this paper, a case study is performed to analyze the initial environmental impacts of producing asphalt mixes with varying amounts of ABR; only the material production phase of the pavement life cycle is analyzed. Asphalt mixes produced in Illinois using differing percentages of RAP and RAS are investigated, and Table 2 displays the ABR mix designs that are used in the case study. A total of 11 mixes are analyzed, with ABR contents ranging from 0% as a control mix to 60%. The functional unit is a one lane-mile of pavement intended to perform equally well in Illinois, where the pavement structure analyzed is a hypothetical pavement lift of 3-inches.

Table 2: Typical ABR Mix Designs

Mix ID	PG-Grade	NMAS (mm)	% Total Binder	% ABR	% Recycled Content				% Voids	G _{mb} , design
					RAP	RAS	RCA	Slag		
Mix 1	58-28	9.5	5.5	49	42	4	--	--	3.0	2.424
Mix 2	58-28	9.5	5.6	59	42	6	--	--	3.0	2.424
Mix 3	58-28	9.5	6.0	25	29	--	--	--	4.0	2.389
Mix 4	58-28	19	6.4	39	30	5	--	--	4.0	2.387
Mix 5	58-28	19	6.0	48	30	5	--	--	4.0	2.383
Mix 6	70-28	9.5	6.1	26	8	5	--	--	3.5	2.405
Mix 7	70-28	9.5	6.0	50	10	8	--	--	3.5	2.405
Control	58-28	19	5.2	--	--	--	--	--	4.0	2.398
Mix 8	58-28	19	5.2	26	30	--	--	--	4.0	2.397
Mix 9	58-28	19	5.2	33	40	--	--	--	4.0	2.401
Mix 10	58-28	19	5.2	41	50	--	--	--	4.0	2.405

Major Assumptions

The first major assumption concerns hauling distances of the raw materials to the HMA plant, which are assumed using average distances for Northern Illinois. The hauling distance is 60 miles for binder and 25 miles for the aggregates. No external transportation is considered for the recycled materials because it is assumed that RAS and RAP are processed on-site at the plant. The second major assumption is that the asphalt binder in all the mixes is modeled with the same straight binder (i.e. PG 64-22 in Illinois) LCI model in the case study. From Table 2, it can be seen that both polymer-modified (PG 70-28) and soft (PG 58-28) binders are used in the mixes. Any additives that are found in these modified binders are not considered, so the environmental burdens from the production of binder may be underestimated.

Results

The total energy consumed and GHG emitted per functional unit of each mix are normalized by the control mix (0% ABR) to observe the effects of varying ABR content. The data included in Figure 2 do not include the feedstock for binder.

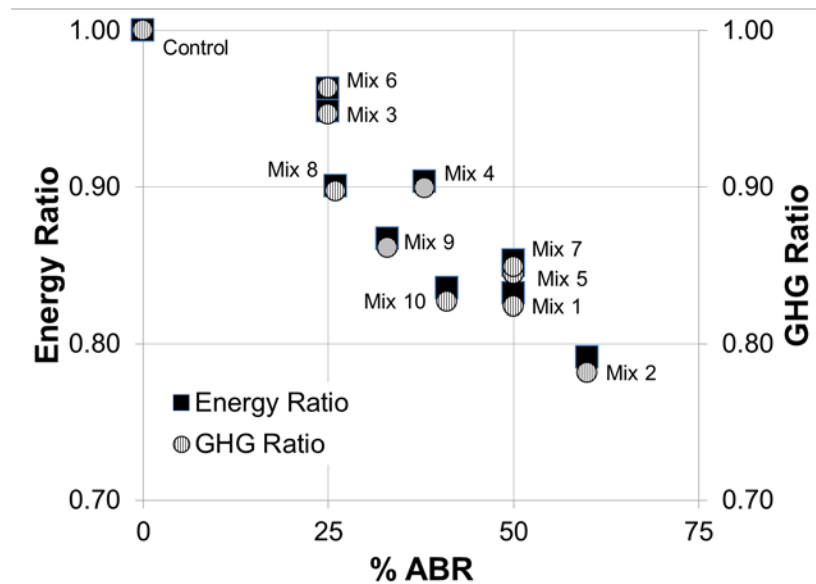


Figure 2: Normalized energy and GHG ratios without feedstock.

A reduction of up to 20.9% in energy and 21.8% in GHGs is observed in the 60% ABR mix (Mix 2). The trend between energy reduction and GHG reduction is linear, as is, to a lesser degree, the relationship between % ABR and the reduction of both impacts. If, however, feedstock of the virgin binder is included in the analysis, the energy consumption decreases more steeply than GHG emissions with respect to increasing ABR content. Figure 3 shows the new trends, where an energy reduction of 46.1% is now seen for the mix with 60% ABR. It must be emphasized that the results are affected by the assumption that the feedstock energy is fully allocated to the virgin binder, with none attributed to RAP or RAS. Thus, Figure 3 represents the largest energy savings possible because a change in allocation will correspondingly alter the savings.

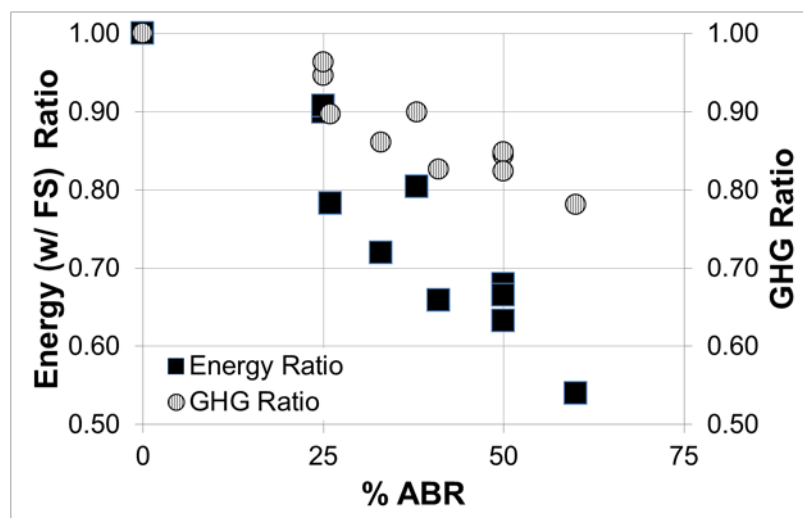


Figure 3: Normalized energy and GHG ratios including feedstock (FS).

The ability of ABR to reduce the environmental impacts in this case study is comparable with that reported in existing studies. For the three 25% ABR mixes analyzed (Mixes 3, 6, 8), there are reductions of 3.7–9.9% energy and 3.7–10.3% GHGs; this is comparable to the U.S. EPA study that found a range of 4.0–18.3% reduction in GHGs for mixes from 20% RAP/0% RAS up to 20% RAP/7% RAS (7). The results from the EPA study were modified to exclude landfill credit and transportation to site to better match the system boundaries in this case study. The reduction found by Athena Institute (3) for producing a 20% RAP rather than 0% RAP mix is lower, with a 4.0% reduction for energy and a 3.5% reduction for GHGs. In addition, the study by Athena Institute also reported the feedstock energy separately. A 15.8% reduction in energy was found, which is within the range of the 9.2–21.7% reduction calculated in this case study for 25% ABR. Although all of these studies had similar system boundaries, there can be various reasons for discrepancies, such as the mix designs themselves, the application of the mixes, and various other assumptions made. For example, for the energy comparison with feedstock energy, Athena Institute takes the binder feedstock energy to be higher at 46.75 MJ/kg as compared to 40.2 MJ/kg for ICT.

Finally, the case study analysis is also run with asphalt binder LCI from each of the literature sources shown in Figure 1. The highest percent reduction in energy and GWP savings for each literature sources occurs with the 60% ABR mix. The relative and absolute reductions in energy and GWP per one 3-inch-lane-mile for the 60% ABR mix are shown in Table 3.

Table 3: Reduction in Energy and GWP for the 60% ABR Case for each Source per 3-inch-lane-mile

Asphalt Binder Model	Energy Reduction		GWP Reduction		Energy with Feedstock Reduction	
	%	GJ	%	tonne CO ₂ e	%	GJ
ICT	20.9	175	21.8	11.4	46.1	1431
Stripple (2)	16.5	122	18.3	8.6	45.8	1379
Häkkinen & Mäkelä (1)	22.5	202	22.1	11.5	46.2	1459
Eurobitume (18)	14.8	105	16.1	7.1	45.7	1362
Athena (17)	25.2	240	27.4	17.1	46.4	1497
US-EI 2.2 (21)	20.6	170	23.6	12.9	46.0	1427

The percent reductions from 0% to 60% ABR mixtures are similar for each source. On the other hand, the absolute reductions differ by up to 135 GJ for energy and 9.9 tonnes CO₂e for GWP. These differences may be compounded over multiple lanes and multiple miles of roadway when evaluating a project. Thus, it is important to consider the most appropriate inventory data available when conducting a LCA. As shown in Table 3, the effect of choosing a regionalized asphalt binder LCI model can have significant effects on the LCA results.

CONCLUSION

In this paper, the development of a regional LCI database was first described for flexible pavement. This database included the production of asphalt binder, recycled materials (RAP and RAS), and coarse and fine aggregates as well as the HMA plant operations. The LCI data were obtained from local questionnaires, literature values, and open source data, which were then modeled using SimaPro and the US-EI 2.2 library. A case study was then conducted to investigate the effect of ABR content on various asphalt mixes used in Illinois. It was found that the reduction of process energy (excluding feedstock) and GHG were linearly related to each other and negatively correlated with increasing ABR content. Reductions of up to 20.9% for

energy consumption, 21.8% for GHGs, and 46.1% for energy including feedstock were observed for a mix with 60% ABR. In addition, it was found that the effect of using different asphalt binder LCI data could cause variations in energy and GHG reductions of up to 135 GJ and 9.9 tonnes CO_{2e} per one 3-inch-lane-mile for a 60% ABR mix.

The data and results given in this paper pertain solely to the material production phase of the pavement life cycle for flexible pavements. Thus, it is necessary to consider the longer-term effects of using recycled asphaltic materials on the performance of the pavement to obtain the complete life cycle impacts of using recycled asphalt materials. The scope of ongoing work involves creating a complete LCA framework and a user-friendly tool for the Illinois Tollway. This tool will cover the entire life cycle of pavements to incorporate the construction, maintenance, use, and EOL phases. In addition, the LCI database for the Northern Illinois region will be expanded to include Portland cement concrete materials, construction equipment, and vehicle emissions.

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