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Quantifying Sustainable Pavements in Virginia—FHWA Climate Challenge Study

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The study evaluated more than 200 Environmental Product Declarations for asphalt mixtures based on data submitted by Virginia asphalt producers. Environmental Product Declarations were analyzed for A1 through A3 emissions and benchmarked against U.S. General Services Administration (GSA) national thresholds. When averaged by four mixture characteristics, most mixture GWP averages were lower than GSA’s national averages, with only one subset that did not meet the GSA’s “Best 20%” GWP criteria. Higher total material extraction and transport emissions (A1 and A2, respectively) were evident in specialty mixtures (e.g., polymer-modified mixtures and stone matrix asphalt). Emissions from material extraction and production (A1 and A3, respectively) typically dominated GWP values for asphalt projects studied. For both cold in-place recycling and full-depth reclamation projects, materials emissions (A1) accounted for most of A1 through A5 emissions—approximately 75% for cold in-place recycling and 97% for full-depth reclamation—primarily due to the high embodied carbon associated with cement production.

As part of the study, the research team also delivered life cycle assessment training to Virginia Department of Transportation staff and produced a roadmap for integrating life cycle assessment and Environmental Product Declaration data into project planning, procurement, and asset management. The roadmap aligns with trends for regional and national climate targets and decarbonization strategies for low-carbon transportation materials. The study recommends that the Virginia Transportation Research Council host a concluding workshop to provide additional training resources and knowledge transfer to Virginia Department of Transportation staff.

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FINAL REPORT

QUANTIFYING SUSTAINABLE PAVEMENTS IN VIRGINIA—FHWA CLIMATE CHALLENGE STUDY

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In Cooperation with the U.S. Department of Transportation
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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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INTRODUCTION

In the United States, the transportation sector is responsible for approximately 29% of the total greenhouse gases (GHG) emitted (Hodges, 2010; U.S. Environmental Protection Agency [EPA], 2021). To confront this challenge, many state and local departments of transportation (DOTs) are creating plans and developing strategies to reduce GHG emissions and promote adopting them. To achieve this goal, DOTs first need to measure and quantify the amount of GHG emissions their infrastructure projects produce.

During the past several decades, the Virginia Department of Transportation (VDOT) evaluated the performance of several technologies that can also help reduce environmental burdens in pavement materials and construction. These technologies include warm mix asphalt (WMA) (Diefenderfer, 2019; Diefenderfer and Hearon, 2008, 2010; Diefenderfer et al., 2007), use of higher reclaimed asphalt pavement (RAP) contents in asphalt mixtures (Diefenderfer et al., 2018; Nair et al., 2019), and cold recycling methods (Bowers et al., 2019; Diefenderfer and Apeagyei, 2014; Diefenderfer et al., 2016, 2019, 2021; Nair and Diefenderfer, 2021), such as cold in-place recycling (CIR), cold central plant recycling, and full-depth reclamation (FDR). In addition, VDOT has assessed the use of high polymer-content asphalt (HP) mixtures, recycling agents, ground tire rubber, hybrid rubber, and recycled plastic (RP) in asphalt mixtures, as well as other additives and modifiers to improve the performance of asphalt mixtures (Bowers et al., 2018; Habbouche et al., 2025; Nair et al., 2022). For concrete pavements, the use of hydraulic limestone cement and higher percentages of supplementary cementitious materials (e.g., fly ash, slag cement, and so on) have been studied to reduce the carbon intensity of concrete pavements (Lane, 2006).

Like many agencies, VDOT does not currently require that the environmental burdens from its projects be quantified. If it needs to do so, the data required to perform such assessments are not readily available in many cases, requiring either the development of such data or the development of the necessary analysis in an open-source format. For these reasons, a need exists to develop these background data to quantify and communicate the environmental impacts and GHG emissions. To promote and encourage the use of this work among state DOTs, the Federal Highway Administration (FHWA) developed a Climate Challenge Program (FHWA, 2022). Members of the research team previously evaluated the effects of multiple pavement recycling projects using life cycle assessment (LCA) methods and participated in a joint effort with the National Asphalt Pavement Association (NAPA) to demonstrate how LCA could be integrated into pavement management system decision-making (Amarh et al., 2021; Lea et al., 2024). In addition, VDOT commissioned a network-wide impact assessment, which included a forward-looking evaluation of decarbonization scenarios, such as vehicle electrification and its implications for GHG emissions (VDOT, 2022). These initiatives have laid important groundwork and highlighted the challenges and opportunities of scaling LCA practices within VDOT's planning, design, and procurement workflows.

Problem Statement

Quantifying the effects of its infrastructure decisions would be difficult for a DOT because most DOTs lack a systematic framework for measuring, reporting, and managing the life cycle impacts of these materials and processes. To help support these future activities, building the internal capacity to evaluate pavement materials using Environmental Product Declarations (EPDs) and LCA is needed. To perform this task, building institutional knowledge, collecting local data, and developing practical tools to support sustainability-driven decision-making are required.

PURPOSE AND SCOPE

This study resulted from an FHWA grant awarded under the Climate Challenge Program. The purpose of this study was to evaluate emissions from different pavement materials and projects through the use of EPDs and LCA to gather information that could be used to build VDOT's capacity to quantify the environmental impacts of pavement materials and construction practices. In addition, the study sought to provide information using tools like EPDs and LCA to support data-driven decisions. Key activities completed during this work included statewide EPD and LCA training, gathering data from case studies that included different pavement technologies, gathering and assessing the effects of different treatments based on LCA, and developing a strategic roadmap for including sustainability into VDOT pavements operations.

METHODS

To complete the work, the research team completed the following tasks:

1. Delivered introductory training to VDOT staff.
2. Established a harmonized LCA framework and a data collection template for materials and paving processes to gather data to support LCA applications.
3. Applied LCA tools to quantify the environmental impacts of pavement materials and processes in terms of GHG emissions for several case studies.
4. Produced a strategic roadmap as an example on how to incorporate LCA into VDOT pavements operations.

Training Workshop

The project began with a training workshop held on March 18, 2024. This training was designed to familiarize VDOT and industry stakeholders with the terms and concepts used during this study and with emerging sustainability policies and practices (Figure 1). Subject matter experts from FHWA and sustainability consultants co-developed the training curriculum. The content included presentations, facilitated discussion, and case study reviews on topics such as FHWA's Sustainable Pavements Program, EPDs, and LCA.

Figure 1. In-person Attendees Participating in the Federal Highway Administration's Climate Challenge Training Workshop at the Virginia Transportation Research Council

Framework and Template for Data Collection and Model Development to Support LCA Applications

To support DOT efforts to evaluate and reduce environmental impacts from pavement materials and construction activities, this study developed a consistent framework for collecting data and building modular LCA models. LCA is a standardized methodology—following

International Organization for Standardization (ISO) 14040/14044—used to quantify the environmental impacts of a product or process during its entire life cycle (ISO, 2006a, 2006b). Pavement LCA typically incorporates four distinct life cycle stages, shown in Figure 2: (1) production (A1, A2, A3); (2) construction (A4–A5); (3) use (B1–B7); and (4) end-of-life (C1–C4) (Harvey et el., 2016). Ideally, any LCA should examine each stage of the product life cycle in detail. However, given time, data, and knowledge constraints, this effort is difficult for most products, including pavements.

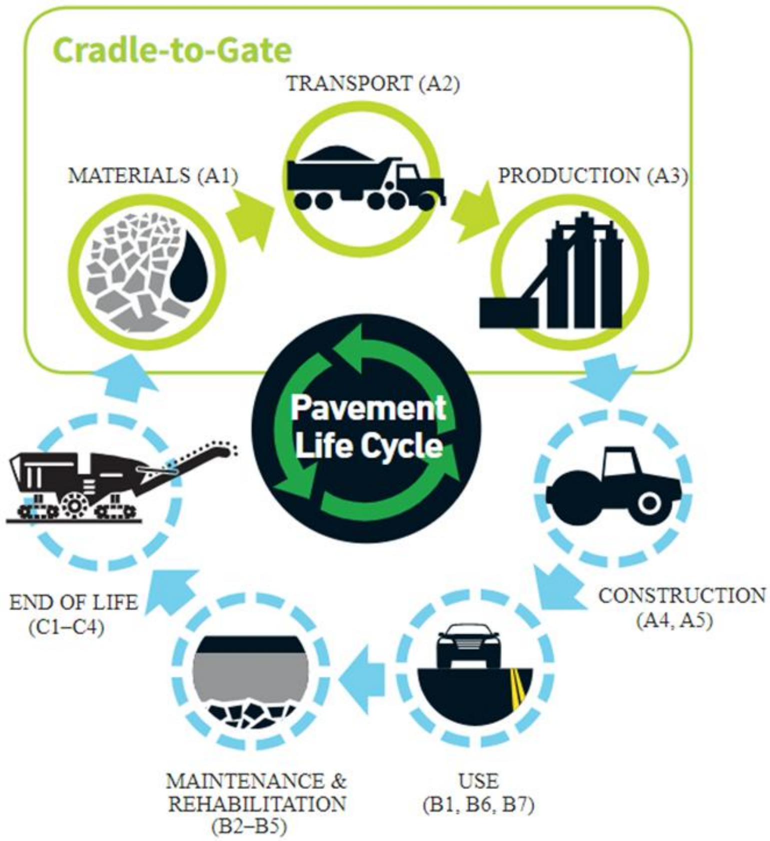


Figure 2. Pavement Life Cycle Stages (Shacat et al., 2022)

The production stage describes the emissions related to activities involved in raw materials acquisition (e.g., mining, crude oil extraction) and processing (e.g., refining, manufacturing, mixing), including transport and plant production. The construction stage describes the emissions related to processes and equipment associated with the construction of pavement systems, including both new construction and reconstruction efforts. The use stage evaluates pavement characteristics (e.g., roughness, stiffness, and macrotexture) that affect vehicle energy consumption and corresponding emissions, as well as the surrounding environment (e.g., hydraulic flow retention or detention and contamination, air emissions, noise, heat capacity and conductivity, solar absorptivity, sound absorptivity). As part of the use stage, maintenance and rehabilitation modules evaluate the emissions related to the application of treatments to an existing pavement that slows the rate of deterioration or that addresses functional or structural deficiencies. The end-of-life stage describes the emissions related to the final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its performance life. In practice, pavements are usually left in place as an underlying layer in their existing condition or are recycled. The scope of this study focuses on life cycle modules A1 through A5. When only modules A1 through A3 are included, the assessment is called *cradle-to-gate*; when A1 through A5 are included, it is termed *cradle-to-laid* or *cradle-to-build*.

Performing an LCA, according to ISO 14044 guidelines, includes four basic steps (Figure 3). These steps include:

- Goal and scope definition—defines the purpose, system boundaries, and functional unit.
- Inventory analysis—quantifies all inputs (e.g., fuel, materials) and outputs (e.g., waste flows and emissions).
- Impact assessment—converts inventory flows into meaningful environmental impact categories (e.g., global warming, acidification, and so on) to better understand their environmental significance.
- Interpretation—synthesizes results to support conclusions and recommendations.

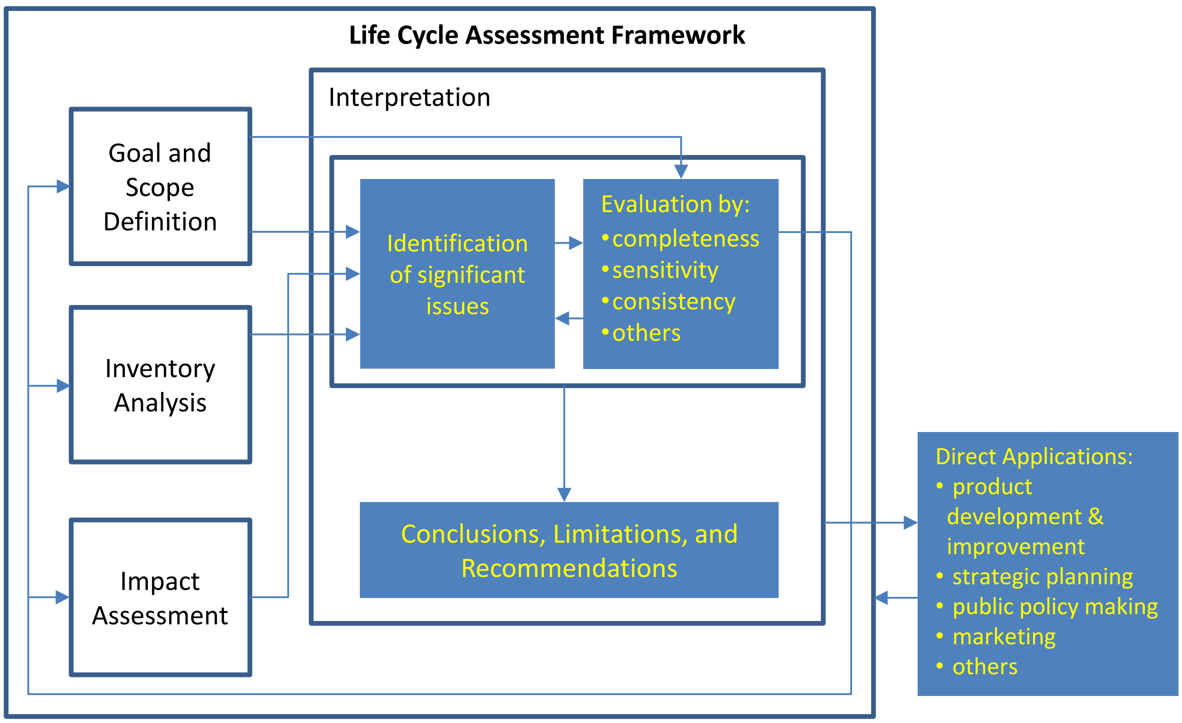


Figure 3. Updated Life Cycle Assessment Framework (adapted from ISO, 2006a)

In this report, the term *global warming potential* (GWP) is used to express the production level embodied GHG emission intensities and is expressed in kg of CO_2 equivalents (kg CO_2e). This nomenclature is done for consistency with other EPD, Product Category Rule, and Buy Clean policy documents, despite this use being inconsistent with how the Intergovernmental Panel on Climate Change and other GHG accounting efforts define GWP (FHWA, 2024).

Conducting a meaningful LCA requires both foreground and background data. *Foreground data* refer to direct, project-specific inputs, such as stabilizer dosage, mixture composition, or equipment fuel use—typically collected through observation, measurements, or agency records (Mukherjee et al., 2020). *Background data* refer to upstream or external processes that are not project-specific, such as emissions from refining asphalt binder or producing electricity (Butt et al., 2019; Mukherjee et al., 2020). These data are often obtained from contractors, third-party databases, and literature sources.

A key concept is the difference between LCA tools and LCA databases. *LCA tools* are software platforms that model pavement systems, perform emissions calculations, and translate data into environmental impacts. Common tools include:

- OpenLCA—open-source and flexible.
- SimaPro and GaBi—commercial tools with large user bases.
- LCA Pave—developed by FHWA for pavement-specific applications.

LCA databases store the life cycle inventory data (inputs and outputs for each process) used by those tools. Key databases include:

- Federal LCA Commons—publicly available, U.S.-specific datasets, including those developed by FHWA, EPA, and other federal agencies.
- Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI)—EPA's Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts, used for impact characterization.
- Ecoinvent and GaBi Databases—widely used global commercial datasets.
- EPDs—product-specific declarations often used to refine background data.

For DOTs, selecting compatible tools and databases is crucial for producing transparent, replicable, and policy-aligned LCA results. This study used OpenLCA, paired with Federal LCA Commons and TRACI impact categories, as well as asphalt mixture EPDs published by NAPA (2022), while also building new modules using real project data to reflect field conditions better.

Development of Standardized Pavement Life Cycle Assessment Models

Although LCA is the primary tool used to evaluate environmental impacts across many material types, its implementation across DOTs for analyzing pavements remains inconsistent, fragmented, and often unsupported by fit-for-purpose tools or datasets. Existing LCA practices and databases frequently rely on non-standardized assumptions, incompatible system boundaries, or generic input values that fail to reflect local conditions or are even missing entire categories, such as pavement recycling techniques like CIR, FDR, and cold central plant recycling. Furthermore, commercial databases such as GaBi or Ecoinvent lack pavement-specific data, forcing practitioners to use proxies or outdated values, reducing confidence in reported results. The absence of harmonized models also makes it difficult to compare alternatives or benchmark emissions across projects.

To fill key data and modeling gaps in how agencies currently evaluate environmental impacts of pavement materials and construction activities, the research team worked to create standardized yet adaptable models within OpenLCA. This work was conducted in collaboration with external partners from Auburn University, Louisiana State University, and Construction

Partners Inc. and staff from Alabama, Mississippi, and Louisiana DOTs. The work builds on the FHWA Asphalt Pavement Framework included in the Federal LCA Commons database (FHWA, 2021; Federal LCA Commons, 2023; Mukherjee, 2023). The resulting models align with the structure of FHWA's LCA Pave tool and are designed to assist practitioners and agencies in quantifying GWP and other environmental impacts from paving operations (FHWA, 2021; Federal LCA Commons, 2023; Mukherjee, 2023).

For this study, the project team used a combination of data from existing databases and developed models to quantify the environmental burdens of the following construction practices:

1. Asphalt mixture production.
2. Asphalt concrete layer construction.
3. CIR base layer construction.
4. FDR base layer construction.
5. Models (3) and (4) with an asphalt concrete overlay.
6. Portland cement concrete production at a mobile plant.
7. Portland cement concrete layer construction.

Emissions models for typical paving practices for the aforementioned practices were developed for use within OpenLCA based on site visits and data collected from several paving projects (Amarh et al., 2025), as this report describes in more detail in following sections. The next section presents a detailed example of Practice 4 (FDR base layer construction).

Framework for Building Standardized Models

Figure 4 is a schematic showing the detailed model of unit processes, or building blocks, used to quantify emissions from one example pavement rehabilitation technique—FDR. For each of the seven practices listed previously, a similar process was followed. Building this model required knowledge of the details within each unit process that are summarized in terms of the life cycle modules (Figure 4).

Material Extraction and Production (A1)

Foreground data for stabilizers and tack coat materials are needed to model emissions associated with the A1 module of the FDR process. These values were estimated from project dimensions or aggregated from production tickets the contractor supplied.

Transport to Production Site (A2)

To model the transportation of materials to the production site (A2), a life cycle inventory developed for single-unit diesel trucks was used as the unit processes. This life cycle inventory is available in the Federal LCA Commons database under the general freight trucking category, as Figure 4 shows (National Renewable Energy Laboratory, 2023). This category agrees with FHWA LCA Pave (FHWA, 2021).

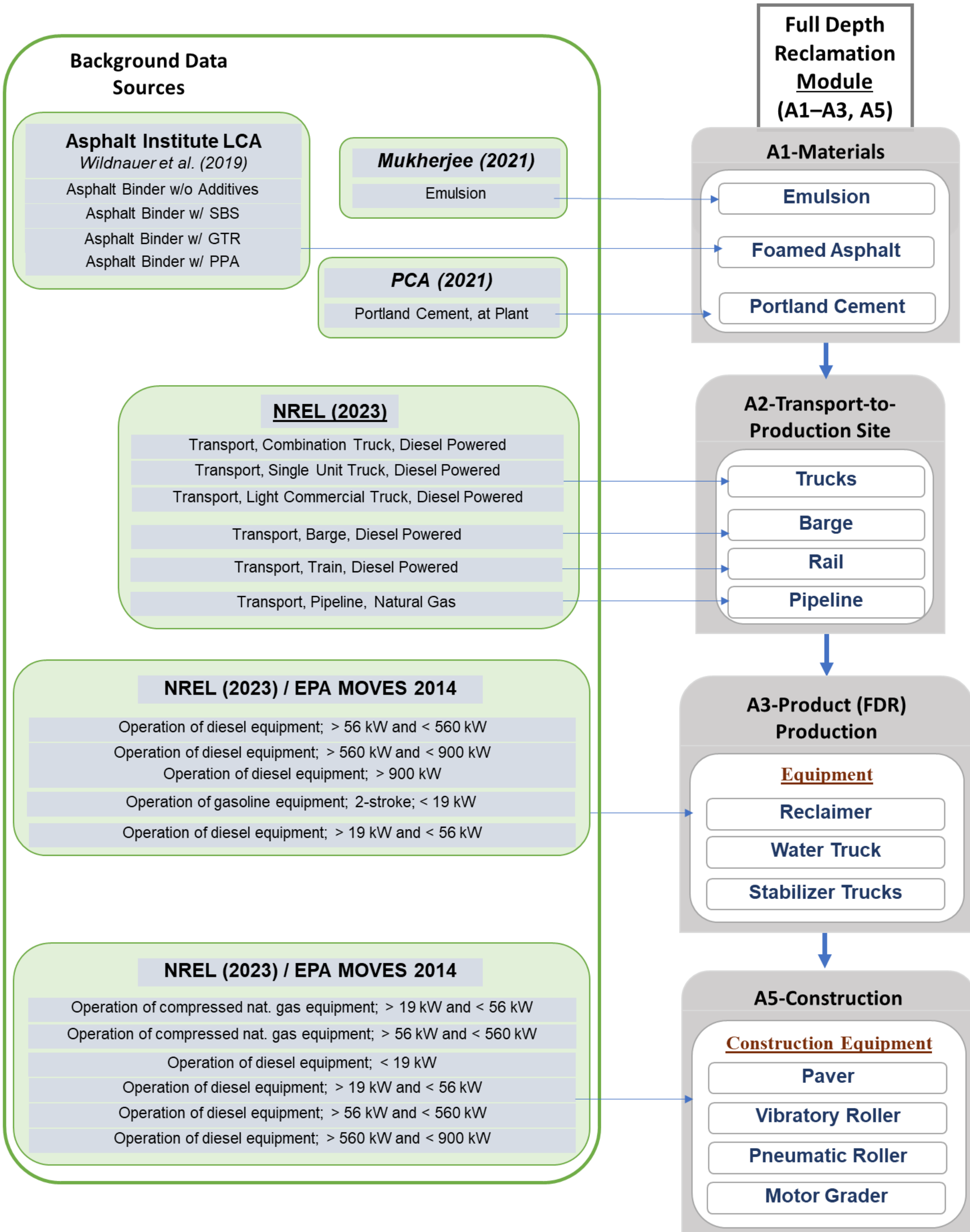


Figure 4. Example Framework for Building FDR Model Showing Unit Process and Life Cycle Modules and Background Data Sources. EPA = U.S. Environmental Protection Agency; FDR = full-depth reclamation; GTR = ground tire rubber; kW = kilowatt; LCA = life cycle assessment; NREL = National Renewable Energy Laboratory; PCA = Portland Cement Association; PPA = polyphosphoric acid; SBS = styrene-butadiene-styrene.

Product Production (A3)

The project team modeled the production of the FDR material (A3) by estimating the energy consumed by the reclaimer (for conventional FDR) or cold recycler (for paver-laid FDR), stabilizer trucks, and water trucks. The contractors can provide fuel use data, or it can be estimated from the production rates of the associated equipment. Figure 4 shows the upstream inventories and unit processes in the A3 module, which were obtained from the EPA Motor Vehicle Emission Simulator model (EPA, 2023). No gaps were noted for these unit processes.

Transport to Construction Site (A4)

No A4 module is associated with the FDR practice because the work is completed in situ.

Construction (A5)

The effects corresponding to the construction module are associated with onsite equipment energy, primarily diesel fuel, used for constructing the FDR material and its associated tailpipe emissions. EPA-developed life-cycle inventories for off-road construction equipment were used as unit processes for modeling the construction equipment operations emissions of the construction module **(**A5**)**, as Figure 4 shows (Randall et al., 2016). The life cycle inventories for onsite construction equipment were derived primarily from the EPA Motor Vehicle Emission Simulator model (EPA, 2023).

Data Collection Forms

To support systematic and consistent data collection, the project team developed custom data collection forms tailored to LCA input needs. These forms were designed to capture foreground data critical to quantifying environmental impact, specifically energy consumption and material quantities related to both production and construction stages. The datasheets focused on estimating total energy use by tracking equipment activity duration (e.g., hours of operation per task) or recording direct energy inputs (e.g., fuel consumption). Appendix Figure A1 shows a sample form for collecting energy use data (foreground data) on an asphalt mill and fill project.

Applying LCA to Quantify GHG Emissions from Pavement Materials and Operations

To understand the environmental performance of pavement materials used in Virginia, the project team undertook a systematic data collection effort to support LCA case studies. The goal of this task was to summarize or generate life cycle inventory data for commonly used and emerging pavement technologies, enabling more accurate quantification of GHG emissions and other environmental impacts. This effort focused on materials and processes currently in use across Virginia, including asphalt mixtures, concrete, and pavement recycling strategies. The data collected under this task formed the foundation for evaluating the embodied effects of different pavement types, informing both environmental benchmarking and potential improvements in material selection and project delivery. This work focused more on asphalt-based materials because this information was more readily available to the project team.

Evaluation of Virginia Asphalt Mixture Environmental Product Declarations

Overview of Environmental Product Declarations

EPDs are standardized, third-party verified documents that report the environmental impacts of construction materials, including GHG emissions, acidification potential, and other categories (Shacat et. al. 20224). EPDs are based on LCA and follow standardized rules called *Product Category Rules*, which ensure the results are consistent and comparable across products. For asphalt mixtures in the United States, NAPA maintains the Product Category Rule (NAPA, 2022), conforming to ISO 14025 and ISO 21930 (ISO, 2017). As of 2024, asphalt EPDs can be generated using NAPA's *Emerald Eco-Label tool*, an online tool that ensures conformance with the Product Category Rule and provides a growing, publicly available repository of verified mix-level environmental data.

The life cycle modules currently included in asphalt EPDs are the production stage, which contains the informational modules A1, raw material extraction and production; A2, transport to the mixture production facility; and A3, mixture production. When including only these three modules, the analysis is commonly referred to as a *cradle-to-gate* analysis. In many cases, EPDs report only these upstream informational modules because the environmental impacts beyond the plant gate (e.g., transportation to site, construction, use, and maintenance) are highly dependent on project-specific variables, which can mostly be outside the manufacturer's control (Miller et al., 2024; Moins et al., 2024; Mukherjee et al., 2020). For example, factors such as traffic levels, base conditions, climate, and agency-specific pavement design and maintenance practices influence the downstream performance of asphalt mixtures.

To support infrastructure decision-making, four types of EPDs are commonly used (Harvey and Butt, 2023):

- Industry-average EPDs—represent the environmental performance of a typical product within the industry.
- Regional-average EPDs—reflect average data within a specific geographic region.
- Product-specific EPDs—apply to a particular product line from a single manufacturer.
- Facility-specific EPDs—represent the effects of a product manufactured at a specific facility by a specific producer.

The distinction between these types is important for application. Industry- and regional-average EPD**s** are typically used during design and to develop benchmarks or policy baselines. In contrast, product- and facility-specific EPDs are critical for procurement decisions—particularly when agencies aim to select lower impact materials or comply with low-carbon procurement policies (Rangelov et al., 2021).

Environmental Product Declaration Evaluation Process

To evaluate the environmental performance of asphalt mixtures produced in Virginia, the project team compiled and analyzed 220 EPDs submitted to the Emerald Eco-Label program as of December 2024. The analysis aimed to understand the influence of production parameters and mix design factors on embodied carbon and to assess how Virginia's asphalt industry compares nationally in terms of emissions performance.

The Inflation Reduction Act directed funding to the U.S. General Services Administration (GSA) and FHWA to incentivize the procurement of low-carbon construction materials, including asphalt mixtures. To operationalize this mandate, EPA developed a tiered evaluation framework aligned with ISO 21678 that defines three benchmarks as (1) top 20%, materials having the lowest emissions, (2) top 40%, and (3) emissions less than national industry averages. Both GSA and FHWA must follow the tiered evaluation framework to develop their threshold values. At the time of this analysis, only GSA had published threshold values, which were consequently used for comparison herein.

To assess Virginia EPDs, the research team subdivided the results by categories relevant to VDOTs pavement practices as follows:

1. Aggregate Structure—This category classifies asphalt mixtures based on aggregate gradation structure: dense graded, open graded, and gap graded (stone matrix asphalt). These aggregate structure types influence binder content, air voids, and mix durability.
2. Pavement Layer Function—Data were further categorized according to their functional placement within the pavement structure—surface mixtures (SMs), intermediate mixtures, base mixtures, and open-graded drainage layer (OGDL). This categorization helps contextualize the environmental data relative to structural design roles.
3. Production Factors—This category grouped mixtures with respect to other attributes that could contribute to changes in emissions, including presence of warm-mix additives, use of balanced mix designs (BMD), and RAP content.
4. Gradation and Binder Factors—Mixtures were also evaluated with respect to nominal maximum aggregate size (NMAS) and binder type, including an evaluation of performance binder grade and binder modifiers.

The evaluation focused on emissions from the cradle-to-gate modules (A1–A3), expressed as kg CO_2 equivalents per short ton of asphalt mixture, and compared these values with GSA thresholds across the classification groups. This comparison allowed a nuanced analysis of how Virginia-produced mixtures perform relative to GSA national decarbonization benchmarks and identified opportunities for improvement or investment.

Life Cycle Assessment Case Studies Data Collection

To assess the environmental performance of pavement materials and construction practices, the project team collected data from a diverse set of case study projects to conduct LCA modeling and analysis. The list of projects shown in Table 1 reflects those projects that were available to the project team during the performance of this work and includes sites that were within and outside the state of Virginia. Certain projects were assessed within the study, but an LCA was not conducted because of significant gaps in available data.

Table 1. List of Projects Identified for LCA Case Studies

Type of Project	State Project No.	Material/Mixture	Date Completed	Project Length (mile)	Project Lane Width (feet)	Project Thickness (inches)
AC Overlay	VA-1	SM-12.5E HP	Sept 2023	0.8	11	2.0
AC Overlay	VA-2	SM-9.5A BMD RP	Oct 2023	1.4	12	1.5
Mill and Overlay	VA-3	SM-12.5A	Sept 2024	6.0	14	2.0
Mill and Overlay	VA-4	BMD-12.5 (40% RAP)	Oct 2023	1.4	24	2.0
Cold In-Place Recycling	CIR-1	EE	June 2021	13.8	12	4
	CIR-2	EE	May 2021	6	11	4
	CIR-3	EE	Sept 2021	13.5	12	4
	CIR-4	EE	May 2021	2.4	14	4
	CIR-5	EE	June 2021	13.2	12	3.5
	CIR-6	EE	Aug 2021	2.6	12	3.2
	CIR-7	EE	Sept 2021	6.5	14	3
	CIR-8	FA	Sept 2021	8	12.5	4
	CIR-9	FA	June 2021	3.5	12	3
	CIR-10	FA	Aug 2021	3.3	11	3
	CIR-11	FA	July 2021	6.3	12	3
	CIR-12	FA	July 2021	14	12	3
	CIR-13	EE+C	Aug 2021	8.7	12	4
	CIR-14	EE+C	July 2021	7.4	11	4
	CIR-15	EE+C	Sept 2021	6.1	14	4
	CIR-16	EE+C	June 2021	3.9	12	4
	CIR-17	EE+C	June 2021	3.6	12	3
	CIR-18	EE+C	Aug 2021	25.7	12	3
	CIR-19	FA+C	June 2021	5.2	16	4
	CIR-20[a]	FA	Sept 2021	5	11	4
Full-Depth Reclamation	VA-1[a]	Cement	June 2023	0.9	12	11.0
	VA-2[a]	Cement	July 2023	0.5	12	10.0
	VA-3[a]	Cement	July 2023	300ft	10	8.0
	VA-4	Cement	June 2023	0.5	12	10.0
PCC Paving	NC-1[a]	PCC	April 2024	52.0	12/25	12.0

AC = asphalt concrete; BMD = balanced mix design; CIR = cold in-place recycling; EE = engineered emulsion; EE+C = engineered emulsion with cement as an active filler; FA = foamed asphalt; FA+C = foamed asphalt with cement as an active filler; HP = high polymer; LCA = life cycle assessment; PCC = Portland cement concrete; RAP = reclaimed asphalt pavement; RP = recycled plastic; SM = surface mixture. [a] Denotes projects that were not quantified because of missing LCA data.

Between June 2023 and April 2024, eight pavement projects were visited in Virginia and North Carolina, encompassing both conventional asphalt resurfacing, FDR operations, and a Portland cement concrete paving project. For all projects, data collection focused on material construction volumes, layer thickness verification, construction sequencing, and fuel use across paving operations. For each project, the project team requested certain data from the contractors to assist with calculating production and construction emissions. As Table 1 shows, some projects were unable to provide all the information required to complete an LCA.

In Virginia, the asphalt resurfacing projects included performance-based mixtures, such as SM-9.5A BMD with RPs, SM-12.5A, and high-polymer SM-12.5E HP, as well as a BMD mixture with 40% RAP. These projects ranged from 0.8 to 6.0 lane-miles in length, with lane widths between 9 and 24 feet and depths of 1.5 to 2 inches. For FDR projects, four projects were visited, including one short 300-foot segment and others up to 0.9 lane-miles in length. These projects provided key data on in-place recycling productivity, cement or bitumen stabilizer use, and specialized equipment such as reclaimers and compactors. Field engagement with contractors allowed for real-time measurement of machine operating hours and material input rates. Figures 5 and 6 show examples of conventional and paver-laid FDR, respectively.

Figure 5. Conventional Full-Depth Reclamation Project on Route 216 Guinea Road in Gloucester County, Fredericksburg

Figure 6. Paver-Laid Full-Depth Reclamation Project on Pitzer Road in Roanoke County

In North Carolina, the site visit targeted a large 52-lane-mile Portland cement concrete paving project with roller-compacted concrete shoulders having paving widths ranging from 12 to 25 feet and depths of approximately 12 inches (Figure 7). This visit enabled the collection of data related to cement and aggregate batching, plant energy demand, concrete delivery logistics, paving train operations, and finishing practices. These observations were needed to model the cradle-to-laid GHG emissions of rigid pavements and understand how Virginia might approach similar projects in the future.

(a)

(b)

Figure 7. Portland Cement Concrete Project on Interstate 540 in Wake County, North Carolina, Showing (a) Concrete Production Site with Mobile Plant and (b) Project Site with Ongoing Paving Operations

For each site visit, the team utilized standardized data collection forms designed to record equipment activity durations, material volumes, fuel consumption, and transportation distances. These forms were completed with support from onsite personnel and plant operators.

This study also included data from a series of CIR projects, using a multi-unit train, constructed outside Virginia. These projects were completed primarily during the 2021 construction season and provided a wide range of CIR design configurations, material specifications, and operational practices. The CIR dataset included project-specific information on lane length, width, depth of treatment, mix designs, and equipment productivity rates. The data also included fuel use measurements or estimates, material volumes, and construction schedules. The contractor or state DOT partners familiar with LCA and sustainability tracking collected these data and organized them in a format compatible with the project's life cycle inventory modeling templates. Figure 8 shows a section of a highway rehabilitated with CIR using a multi-unit train.

Figure 8. Multi-Unit Cold In-Place Recycling Train

Data collection forms were distributed in advance of site visits or data requests and often completed in collaboration with field staff or plant operators. The completed forms served as a critical input for generating life cycle inventory models in OpenLCA, enabling consistent comparison of embodied GHG emissions across technologies.

Quantifying Environmental Impacts of Case Study Projects

The goal of the LCA project's case study was to quantify the global warming impacts using data collected from the various paving projects as a benchmark for Virginia. The methodology followed the FHWA's Pavement Life Cycle Assessment Framework (Harvey et al., 2016). The system boundary was A1 through A5 for those projects involving paving operations, with a declared unit of 1 short-ton of mix paved for the Virginia asphalt paving projects and 1 lane-mile for the FDR and CIR projects. Hauling construction equipment was not included in the system boundaries.

The OpenLCA models developed as part of this study were used in the analysis with foreground datasets collected from individual projects and background datasets from the Federal LCA Commons repository and the Ecoinvent database in cases when data were not available in LCA Commons. Version 2.0 of TRACI, which is included as part of the OpenLCA software, was used to conduct the impact assessment, reporting global warming as the primary impact.

The results of the impact assessments were analyzed using a combination of statistical techniques and Pareto analysis to evaluate both total and average environmental impacts across all case study projects. The analysis included a detailed examination of the contribution of individual life cycle modules, such as raw material production, transportation, and construction, to determine the overall effects. Within each module, unit processes and material inputs were further assessed to identify the primary drivers of GWP.

Roadmap Development

To institutionalize LCA and EPD practices within any agency, a roadmap was proposed as part of this project. The roadmap was intended to guide agencies in transitioning from preliminary GHG benchmarking to full-scale integration of environmental sustainability into project planning, materials procurement, and pavement management.

RESULTS AND DISCUSSION

Training Delivery Summary

The training was conducted on March 18, 2024, with participation from VDOT executives, engineers, and project delivery personnel. The primary objective of the session was to increase institutional awareness in relation to FHWA's evolving sustainability initiatives. More specifically, the training sought to familiarize participants with the role of EPDs in green procurement and the implications of carbon emissions tracking programs. During the training session, participants received an overview of EPDs and LCA. Participants were introduced to the process of developing EPDs, the role of Product Category Rules, and the use of EPDs in benchmarking and procurement decisions.

During the training, participants also learned about several case studies, including work conducted by the Colorado DOT, which has implemented EPD requirements via state legislation. The presentation detailed the DOT's timeline for policy development, its focus on precast concrete and asphalt materials, and the development of bid item tracking tools and special provisions. Participants learned how Colorado DOT has supported industry through outreach, training, and resource development. In addition, activities in Sweden, the Netherlands, and Norway were also discussed. These countries have integrated green public procurement practices for more than a decade, including tools like bonus-incentive systems, which are tied to EPD-based environmental performance.

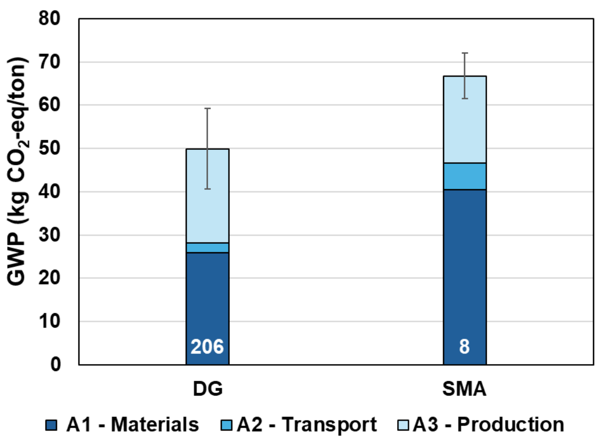
Results for Life Cycle Assessment Case Studies

Virginia Asphalt Mixture Environmental Product Declaration Trends

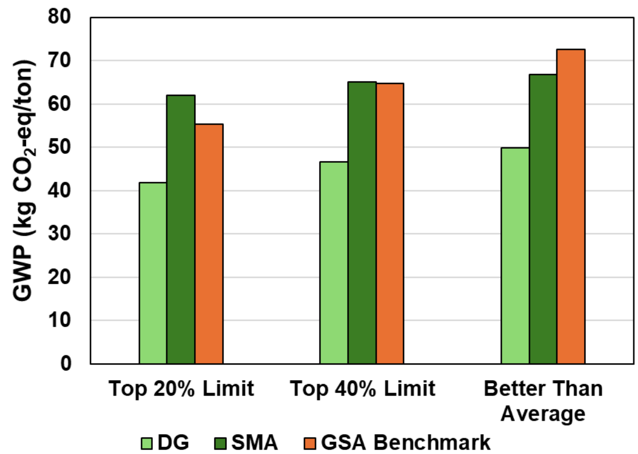
The environmental performance of asphalt mixtures used across Virginia were analyzed by evaluating the collected EPDs. The EPDs were organized into four functional groups: (1) aggregate structure; (2) pavement layer function; (3) production factors; and (4) production and binder factors. Each grouping allowed comparison of GWP across different design strategies and material configurations, with emissions allocated to raw materials extraction (A1), transport (A2), and mixture production (A3).

Aggregate Structure

Aggregate gradation structure-based classifications revealed a contrast between dense-graded and stone matrix asphalt mixtures (Figure 9a). The dense-graded mixtures had an average GWP of 49.9 kg CO_2-eq/ton, whereas stone matrix asphalt mixtures had an average GWP of 66.8 kg CO_2-eq/ton. Higher materials and transport emissions (A1 and A2, respectively) caused the increased GWP for stone matrix asphalt mixtures. This outcome was not unexpected, given that stone matrix asphalt mixtures typically have higher binder contents than dense-graded mixtures. The dense-graded mixtures met all thresholds compared with the GSA benchmarks (Figure 9b). Stone matrix asphalt mixtures met the Industry Average and Best 40% thresholds but did not satisfy the more stringent Best 20% Limit.



(a)

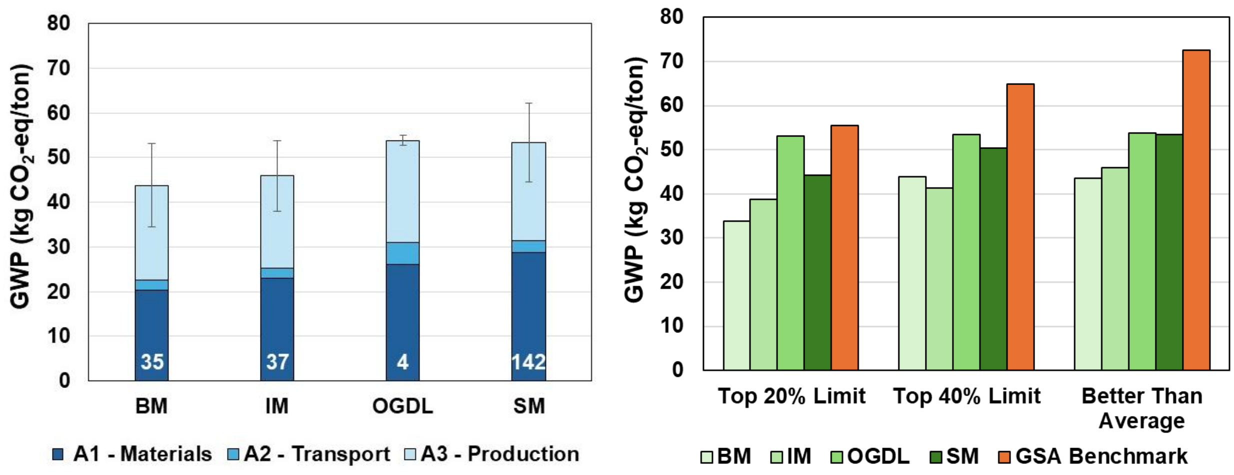


(b)

Figure 9. Results for Gradation-Based Mix Types Showing (a) Average of Virginia Asphalt Mixture EPDs by Production Stage Module. The number of EPDs used in computing the average GWP is highlighted in the base of each column. Error bars represent plus or minus 1 standard deviation of the total GWP. (b) Comparison of percentiles for Virginia and national General Services Administration benchmarks. DG = dense graded; EPDs = Environmental Product Declarations; GWP = global warming potential; SMA = stone matrix asphalt.

Pavement Layer Function

Differences in emissions related to base mixtures, intermediate mixtures, and SMs, in addition to OGDL, were also evaluated. Base mixtures showed the lowest average GWP (43.5 kg CO_2-eq/ton), whereas SMs and OGDL had higher average GWP, both at 53.7 kg CO_2-eq/ton. However, the differences in average GWP between base mixtures, intermediate mixtures, and SMs were not statistically significant (Figure 10a). The production emissions (A3) remained consistent across layer types, but materials emissions (A1) were the main drivers of variation. The entire group of mixtures met the GSA Top 20% thresholds compared with the GSA benchmarks (Figure 10b).



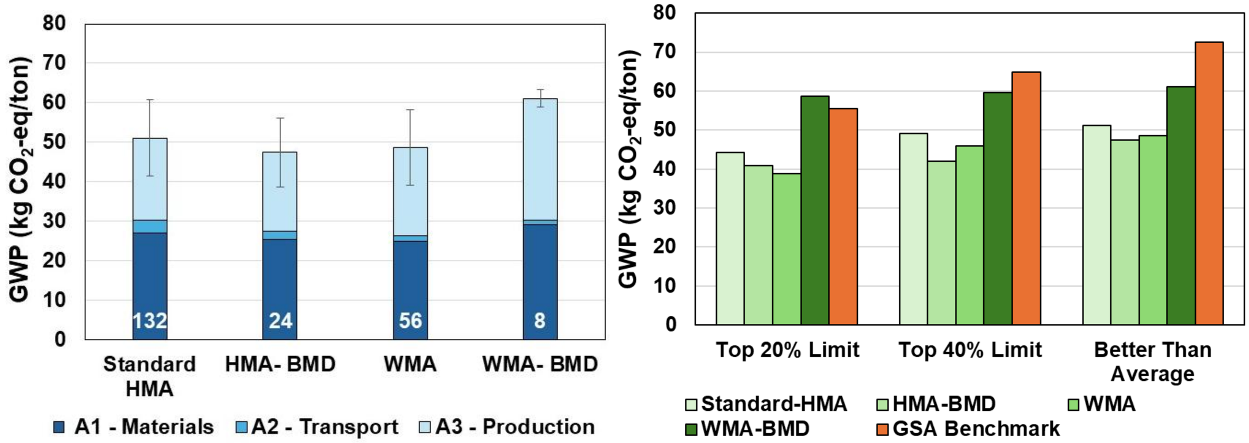
(a) (b)

Figure 10. Results by Pavement Layer Function Showing (a) Average of Virginia Asphalt Mixture EPDs by Production Stage Module. The number of EPDs used in computing the average GWP is highlighted in the base of each column. Error bars represent plus or minus 1 standard deviation of the total GWP; (b) comparison of percentiles for Virginia and national General Service Administration benchmarks. BM = base mixture; EPDs = Environmental Product Declarations; GWP = global warming potential; IM = intermediate mixture; OGDL = open-graded drainage layer; SM = surface mixture.

Production Factors

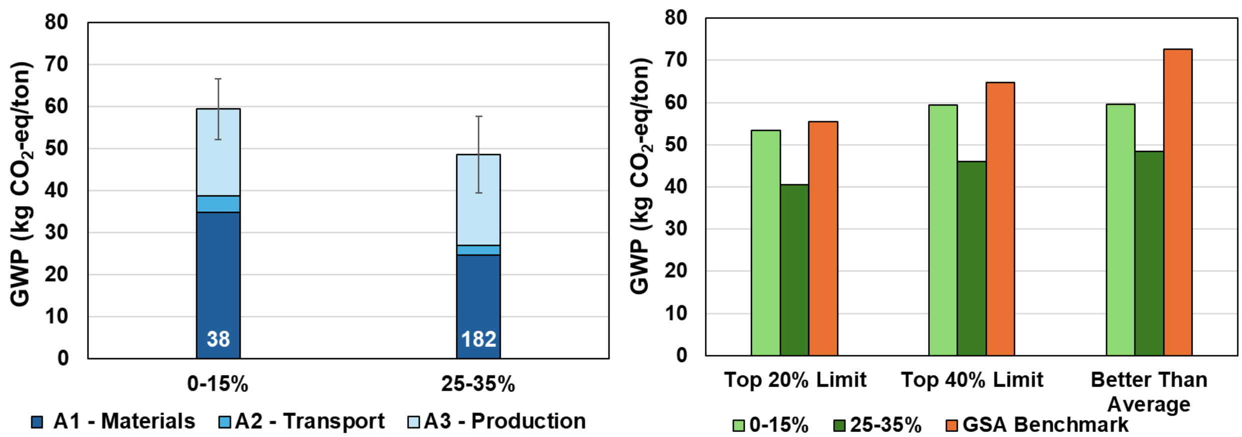
This group included four mixture types: (1) standard hot mix asphalt (HMA); (2) HMA BMD; (3) WMA; and (4) WMA BMD. The lowest average GWP was observed for HMA BMD (47.4 kg CO_2-eq/ton), driven by slightly reduced emissions from all three modules (Figure 11a). However, the difference in average GWP between HMA, HMA BMD, and WMA mixtures was found to be not statistically significant. WMA BMD exhibited the highest average GWP (61.1 kg CO_2-eq/ton) because of elevated production emissions (A3), but only eight mixtures were included in this group. It is unclear if this result is indicative of an overall trend. Interestingly, although WMA technologies are often associated with energy savings, reduced production emissions (A3) were not found likely because the NAPA LCA process accounts for annual production emissions rather than mixture-specific emissions. All mixture types met the Best 20% Limit except for the WMA BMD mixtures compared with the GSA benchmarks (Figure 11b).

Mixtures were also grouped by low (0–15%) and high (25–35%) RAP contents. The higher RAP mixtures (25–35%) showed lower average GWP (48.5 kg CO_2-eq/ton) compared with the lower RAP group (59.6 kg CO_2-eq/ton), as Figure 12a shows. This result supports the widely held understanding that higher RAP contents can reduce materials emissions (A1). Materials emissions (A1) in the lower RAP group were considerably higher than the higher RAP group (34.8 kg CO_2-eq/ton versus 24.6 kg CO_2-eq/ton). The entire group of mixtures met the Top 20% threshold compared with the GSA benchmarks (Figure 12b).



(a) (b)

Figure 11. Results for Production Factors Showing (a) Average of Virginia Asphalt Mixture EPDs by Production Stage Module. The number of EPDs used in computing the average GWP is highlighted in the base of each column. Error bars represent plus or minus 1 standard deviation of the total GWP. (b) Comparison of percentiles for Virginia and national General Service Administration benchmarks. BMD = balanced mix design; EPDs = Environmental Product Declarations; GWP = global warming potential; HMA = hot mix asphalt; WMA = warm mix asphalt.



(a) (b)

Figure 12. Results for Reclaimed Asphalt Pavement Contents Showing (a) Average of Virginia Asphalt Mixture EPDs by Production Stage Module. The number of EPDs used in computing the average GWP is highlighted in the base of each column. Error bars represent plus or minus 1 standard deviation of the total GWP. (b) Comparison of percentiles for Virginia and national General Services Administration benchmarks. EPDs = Environmental Product Declarations; GWP = global warming potential.

Gradation and Binder Factors

Comparing mixtures with NMAS greater than 12.5 mm and NMAS less than or equal to 12.5 mm revealed that larger NMAS mixtures had a lower average GWP (45.2 kg CO_2-eq/ton) compared with smaller NMAS mixtures (53.4 kg CO_2-eq/ton), as Figure 13a shows. This outcome was found to be largely due to a difference in the materials emissions (A1) and is thought to be related to typically lower binder contents and use of higher RAP contents in larger NMAS mixtures. Both mixture types had nearly identical material transport (A2) and production

(A3) emissions. The group of mixtures met the Top 20% threshold compared with the GSA benchmarks (Figure 13b).

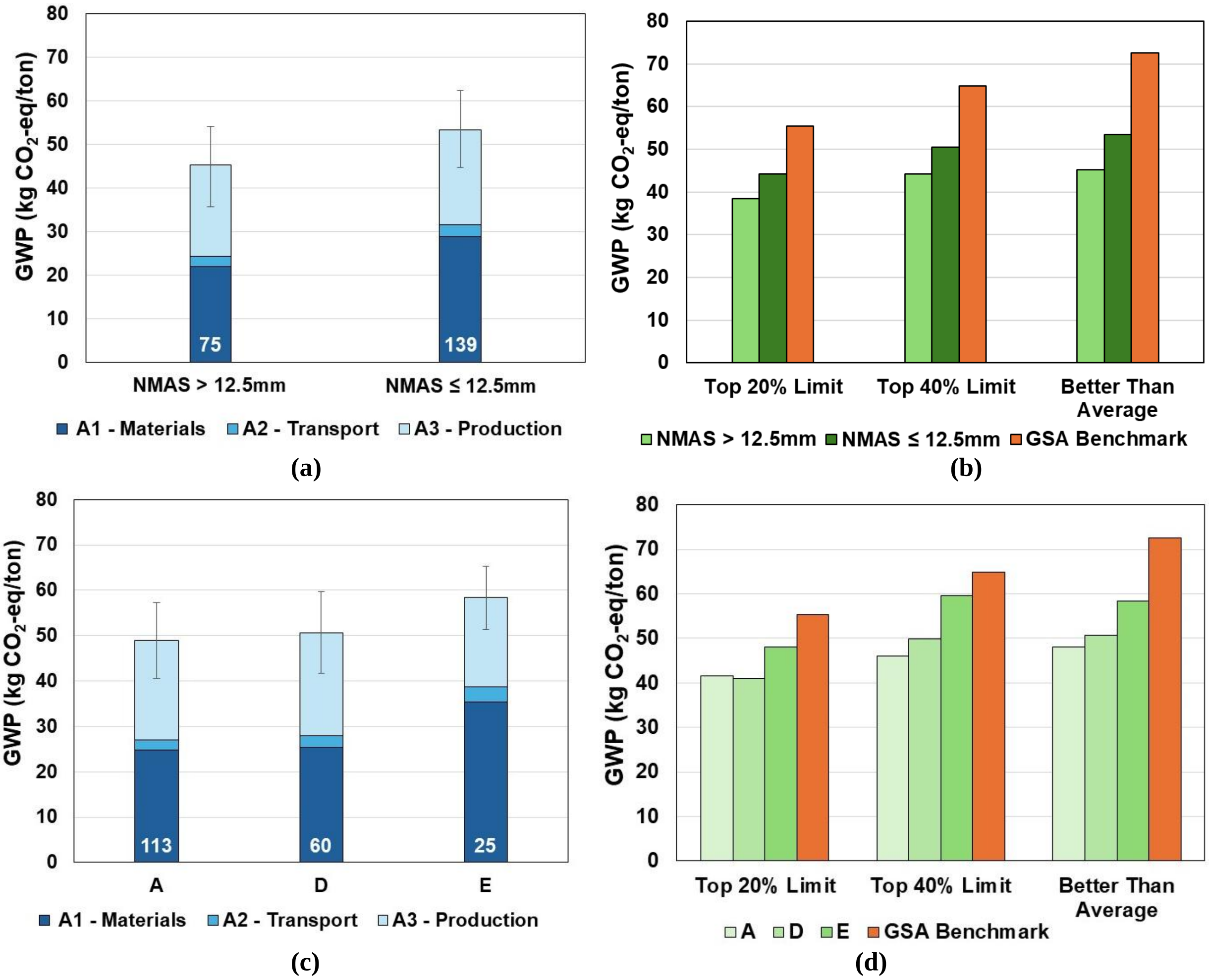


Figure 13. Results for NMAS and Binder Type Showing (a) Average of Virginia Asphalt Mixture EPDs by Production Stage Module. The number of EPDs used in computing the average GWP is highlighted in the base of each column. Error bars represent plus or minus 1 standard deviation of the total GWP. (b) Comparison of percentiles for Virginia and national General Services Administration benchmarks. (c) Average of Virginia asphalt mixture EPDs by production stage module. The number of EPDs used in computing the average GWP is highlighted in the base of each bar. (d) Comparison of percentiles for Virginia and national General Services Administration benchmarks. EDPs = Environmental Product Declarations; GWP = global warming potential; NMAS = nominal maximum aggregate size.

VDOT uses the designations A, D, and E to represent 64S-22, 64H-22, and 64V-22 binders, respectively (VDOT, 2020). When grouped by binder category, performance-grade binders showed varied GWP results (Figure 13c). The difference in GWP when comparing mixtures using A and D binders was found to be not statistically significant (48 and 49 kg CO_2-eq/ton, respectively). Binder Type E, which is defined as being polymer modified, recorded the highest total GWP at 58.4 kg CO_2-eq/ton, mostly due to increased materials emissions (A1). The group of mixtures met the Top 20% threshold compared with the GSA benchmarks (Figure 13d).

Comparison by VDOT District

Figure 14 presents a comparison of Virginia asphalt mixture EPDs by district and by GSA benchmarks. Asphalt producers in two VDOT districts (Staunton and Culpeper) had not submitted any EPDs at the time of the analysis.

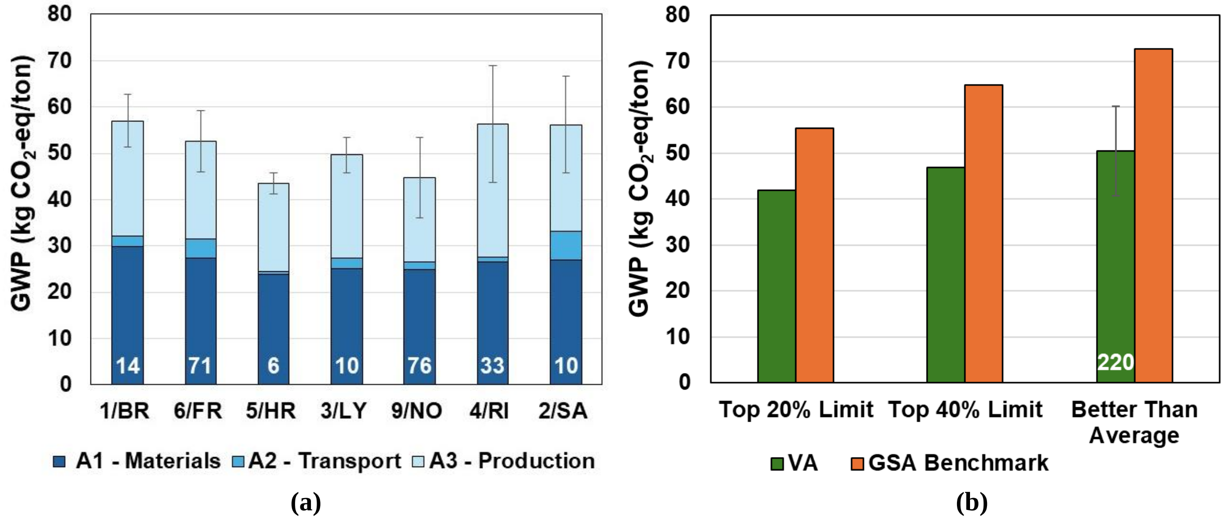


Figure 14. Results Showing (a) Average of Virginia Asphalt Mixture EPDs by Production Stage Module. The number of EPDs used in computing the average GWP is highlighted in the base of each column. Error bars represent plus or minus 1 standard deviation of the total GWP. (b) Comparison of percentiles for Virginia and national General Services Administration benchmarks. BR = Bristol District; EPDs = Environmental Product Declarations; FR = Fredericksburg District; GWP = global warming potential; HR = Hampton Roads District; LY = Lynchburg District; NO = Northern Virginia District; RI = Richmond District; SA = Salem District.

An evaluation of EPD data by VDOT districts revealed some regional differences in average GWP (Figure 14a). Among the seven districts analyzed, Hampton Roads exhibited the lowest average GWP, 43.5 kg CO_2-eq/ton, reflecting lower impacts across all life cycle modules. Bristol, Richmond, and Salem Districts reported the highest average GWP values, each exceeding 56 kg CO_2-eq/ton. Richmond recorded the highest mixture production (A3) emissions, averaging 28.7 kg CO_2-eq/ton. Transport-related emissions (A2) were highest in the Salem (6.1 kg CO_2-eq/ton) and Fredericksburg (4.0 kg CO_2-eq/ton) Districts. Given the relatively low number of mixtures cited for several of the districts (10 or fewer in 3 districts), it is difficult to reasonably attribute differences to any one factor. These results should be re-evaluated when additional EPDs are available for more districts and further information, such as plant location and source material distances or average GWP by similar mix types, are available.

As Figure 14b shows, the average GWPs from all Virginia mixtures are well below the Top 20% threshold compared with the national benchmarks.

Life Cycle Assessment Case Studies

Summary of Data Collected

Contractors provided data in the form of aggregated daily or weekly fuel use summaries for each piece of construction equipment. These summaries allowed the project team to assign equipment to one of the LCA modules. The project team considered this assignment advantageous for calculation purposes. Fuel use was tracked either by automated equipment logging or by refueling equipment after each workday and documenting the fuel added. This fuel use data were paired with production metrics such as square yards completed or tons of material processed.

Table 2 summarizes the quantities of key materials, transportation distances, and energy consumption for various Virginia asphalt and specialty mixtures. The dataset captures data from paving projects with asphalt mixtures, including SM-12.5E HP, SM-9.5A BMD RP, BMD-12.5 (40% RAP), and SM-12.5A, illustrating variability in material intensities (e.g., binder and aggregate tonnages) and transportation distances under real-world conditions.

Table 2. Summary of Data Collected for Virginia Asphalt and Specialty Mixtures for Entire Project

Life Cycle Module	Materials	Unit	SM-12.5E HP	SM-9.5A BMD RP	BMD-12.5 40% RAP	SM-12.5A
A1	Additives	tons	0.9	0.4	-	0.1
	Aggregates	tons	1,062.9	1,367.0	967.6	4,626.2
	Binder	tons	72.5	87.0	60.9	327.6
	Filler	tons	-	-	-	427.5
	Other = Plastic	tons	-	3.6	-	-
	RAP	tons	-	-	645.1	
	Water	tons	-	-	1,000.0	-
A2	Additives	miles (one-way)	unavailable	1,000.0	-	0.0
	Aggregates	miles (one-way)	23.6	63.0	-	0.75
	Binder	miles (one-way)	74.1	8.7	252.0	68
	Filler	miles (one-way)	-	-	-	0.3
	Other = Plastic	miles (one-way)	-	2,000.0	-	-
	RAP	miles (one-way)	-	-	0.0	0.0
	Water	miles (one-way)	-	-	15.0	-
A3	Asphalt Mixture	tons	1,250.5	1,447.0	1,673.6	5,836.5
	RFO	gallons				7,004
	Diesel	gallons				3,620
	Natural Gas	CCF	689	339.0	unavailable	-
A4	Asphalt Mixture	miles (one-way)	52	36	-	53.9
A5	Total Paving Equipment Fuel Used	gallons/ mix ton	0.52	0.20	-	0.60

BMD = balanced mix design; CCF = hundred cubic feet; HP = high polymer; PCC = Portland cement concrete; RAP = reclaimed asphalt pavement; RFO = recycled fuel oil; RP = recycled plastic; SM = surface mixture.

Table 3 presents detailed data for CIR and FDR projects, capturing RAP quantities, fuel consumption, and transportation metrics from the projects assessed within this study. These data highlight differences in project scales, material flows, and construction energy demands inherent to in-place recycling technologies.

Table 3. Summary Data Collected for Cold In-Place Recycling and Virginia Full-Depth Reclamation Projects for Entire Project

Type	Project No.	Thickness	RAP Qty	A1				A2				A3	A5
				C	EE	FA	W	C	EE	FA	W	Diesel Fuel	
		in.	tons				k-gals	miles				gallons	
CIR-EE	CIR-1	4	28,670	-	684	-	230		102		12	4,950	1,329
	CIR-2	4	24,039	-	454	-	127	-	49	-	7	4,313	1,481
	CIR-3	4	51,643	-	696	-	174	-	113	-	8	6,932	1,932
	CIR-4	4	5,481	-	80	-	23	-	219	-	6	1,084	356
	CIR-5	3.5	32,962	-	630	-	118	-	59	-	12	4,393	1,761
	CIR-6	3.2	11,005	-	201	-	62	-	-	-	4	2,293	715
	CIR-7	3	13,632	-	304	-	67	-	373	-	7	2,469	828
CIR-FA	CIR-8	4	26,618	-	-	453	112	-	37	-	7	3,755	494
	CIR-9	3	7,193	-	-	144	65	-	67	-	8	1,353	423
	CIR-10	3	10,129	-	-	141	135	-	-	71	5	1,477	320
	CIR-11	3	20,715	-	-	227	130	-	-	118	6	2,540	429
	CIR-12	3	43,463	-	-	472	340	-	-	48	8	5,307	1,015
CIR-EE+C	CIR-13	4	29,272	154	669	-	148	37	154	-	8	1,555	469
	CIR-14	4	23,892	114	523	-	120	85	202	-	6	3,704	811
	CIR-15	4	30,509	103	630	-	110	68	149	-	4	2,524	522
	CIR-16	4	26,687	211	575	-	113	82	64	-	6	3,420	924
	CIR-17	3	6,385	23	91	-	45	30	30	-	2	1,465	297
	CIR-18	3	74,465	301	1,729	-	400	126	316	-	8	10,416	2,451
CIR-FA+C	CIR-19	4	28,857	194		434	104	145	-	42	9	3,754	748
FDR-C	VA	11	7,700[a]	106			12	18			0.5		598

[a] Calculated from project dimensions. C = cement; CIR = cold in-place recycling; EE = engineered emulsion; EE+C = engineered emulsion with cement as an active filler; FA = foamed asphalt; FA+C = foamed asphalt with cement as an active filler; RAP = reclaimed asphalt pavement; W = water.

Figure 15 illustrates the relationship between total fuel use (gallons) in modules A3 and A5 and the quantity of recycled material processed (tons) across multiple CIR projects. A strong correlation exists between the quantity of recycled materials and fuel use across all projects, indicating that fuel consumption generally scales with the amount of processed materials. The correlation coefficient with respect to stabilization type was greater than 0.96. This analysis of fuel use versus quantity of recycled material processed helps demonstrate how equipment energy consumption scales with material output across projects, supporting better estimates of environmental impacts in the absence of complete EPDs. By understanding this relationship, VDOT and other agencies can easily benchmark performance, identify outliers, and guide more efficient planning, equipment use, or project design choices in future pavement recycling initiatives.

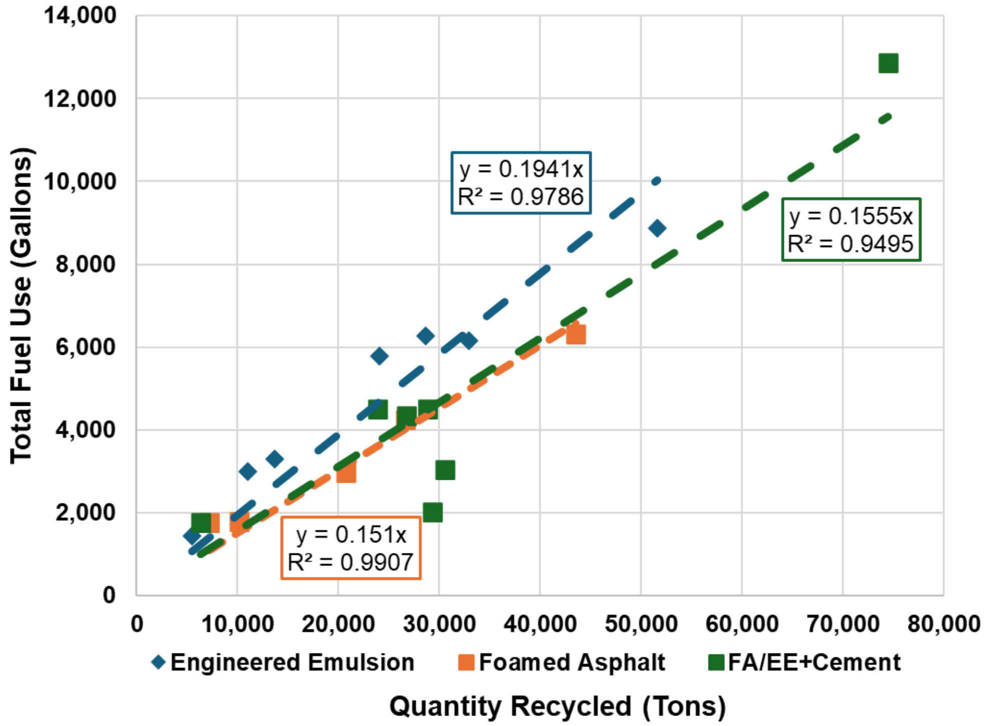


Figure 15. Relationship between Total Fuel Use (Gallons) and Quantity of Recycled Material Processed (Tons). EE = engineered emulsion; FA = foamed asphalt.

Project-Level Global Warming Potential Results—Virginia Asphalt Paving Projects

Figure 16 highlights the GWP per mix-ton for the asphalt mixture paving projects studied in Virginia. Materials (A1) and production (A3) emissions remained the largest contributors, together accounting for approximately 70 to 85% of the total GWP across all projects evaluated. The materials module (A1) from Figure 16a contributed similar levels of emissions across all three projects, ranging from 33.7 to 38.1 kg CO_2-eq/mix-ton. The emissions related to production of RP and polymer used in the SM-9.5A BMD RP and SM-12.5E HP mixtures, respectively, are not well defined nationally and are thus not included in this result. More noticeable differences were observed for transport (A2) in Figure 16b. The SM-9.5A BMD RP overlay project had the highest A2 emissions at 19.8 kg CO_2-eq/mix-ton, mostly due to long aggregate haul distances (64 miles). By comparison, the Mill and Overlay project using SM-12.5A recorded the lowest A2 emissions at 0.8 kg CO_2-eq/mix-ton, reflecting the use of a nearby aggregate source just 0.75 miles away. In production (A3) from Figure 16c, the SM-12.5E HP overlay project showed the highest emissions at 54.6 kg CO_2-eq/mix-ton. This result is likely linked to the use of polymer-modified binder, which typically requires higher production temperatures and longer mixing times (Butt et al., 2016; Shacat et al., 2022). The Mill and Overlay project had a moderate A3 value of 27.6 kg CO_2-eq/mix-ton, and the BMD RP overlay was lowest at 16.2 kg CO_2-eq/mix-ton. The A1 through A3 emissions for these three mixtures range from 62.1 to 95.7 kg CO_2-eq/mix-ton. These values are similar to the upper end of the cradle-to-gate range of emissions from SMs identified in the analysis of EPDs (25.1 to 75.0 kg CO_2-eq/mix-ton).

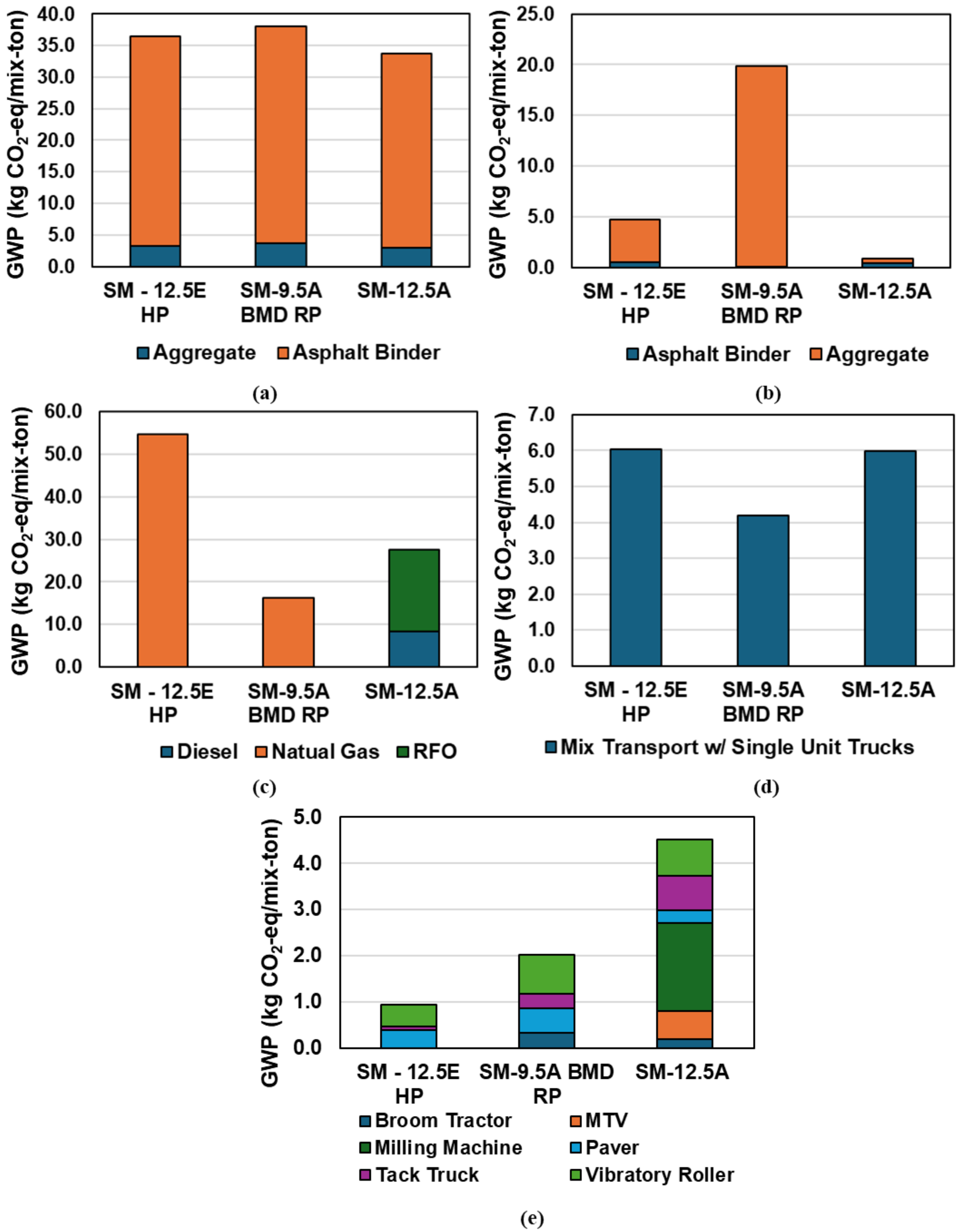


Figure 16. Results for Conventional and Specialty Asphalt Mix Projects Showing Details of (a) A1-Material Extraction and Production; (b) A2-Transport to Production Site; (c) A3-Production of Mixtures; (d) A4-Transport to Site; (e) A5-Construction. Life Cycle Assessment Omits Results from Extraction and Production of Recycled Plastics and Polymers Modifiers. BMD-12.5 (40% reclaimed asphalt pavement) not included due to missing data. BMD = balanced mix design; GWP = global warming potential; HP = high polymer; MTV = material transfer vehicle; RFO = recycled fuel oil; RP = recycled plastic; SM = surface mixture.

Transport emissions (A4) shown in Figure 16d were similar across projects, ranging from 4.2 to 6.0 kg CO_2-eq/mix-ton. However, construction emissions (A5) showed more variation (Figure 16e). The Mill and Overlay project recorded the highest A5 value at 4.5 kg CO_2-eq/mix-ton, likely due to the use of a material transfer vehicle and milling machine that were not reported for the other projects. The SM-12.5E HP overlay had the lowest construction emissions at 0.9 kg CO_2-eq/mix-ton.

In terms of total GWP, Figure 17 shows that the SM-12.5E HP project had the highest impacts at 103 kg CO_2-eq/mix-ton, mainly because of the higher production (A3) emissions. The BMD RP overlay followed with 80 kg CO_2-eq/mix-ton, influenced by greater transport emissions (A2). The Mill and Overlay project had the lowest total GWP at 73 kg CO_2-eq/mix-ton, benefiting from lower transport emissions (A2), although with higher construction emissions (A5).

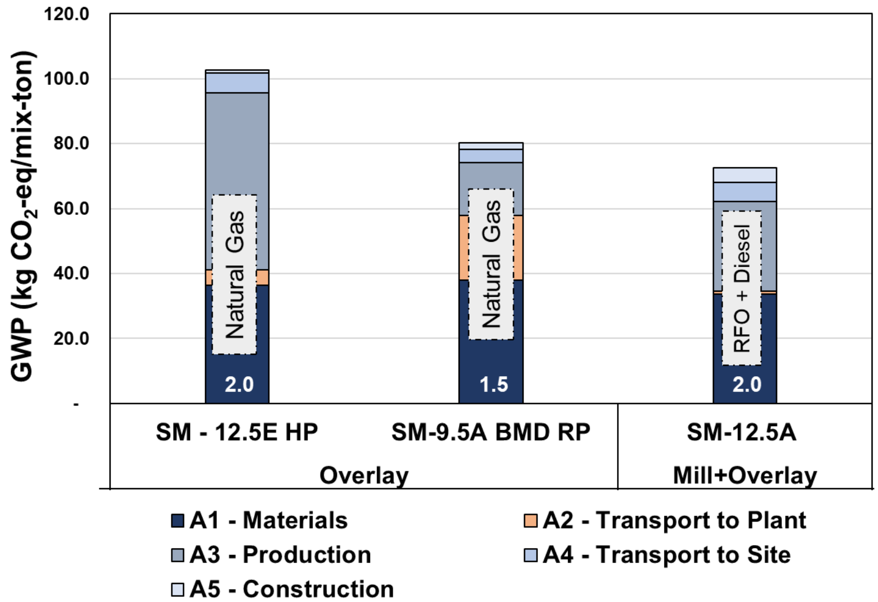


Figure 17. Results for Conventional and Specialty Asphalt Mix Projects Showing Totals by Production and Construction Stage Modules. Life cycle assessment omits results from extraction and production of recycled plastics and polymer modifiers. BMD-12.5 (40% reclaimed asphalt pavement) not included due to missing project data. BMD = balanced mix design; GWP = global warming potential; HP = high polymer; RP = recycled plastic; SM = surface mixture.

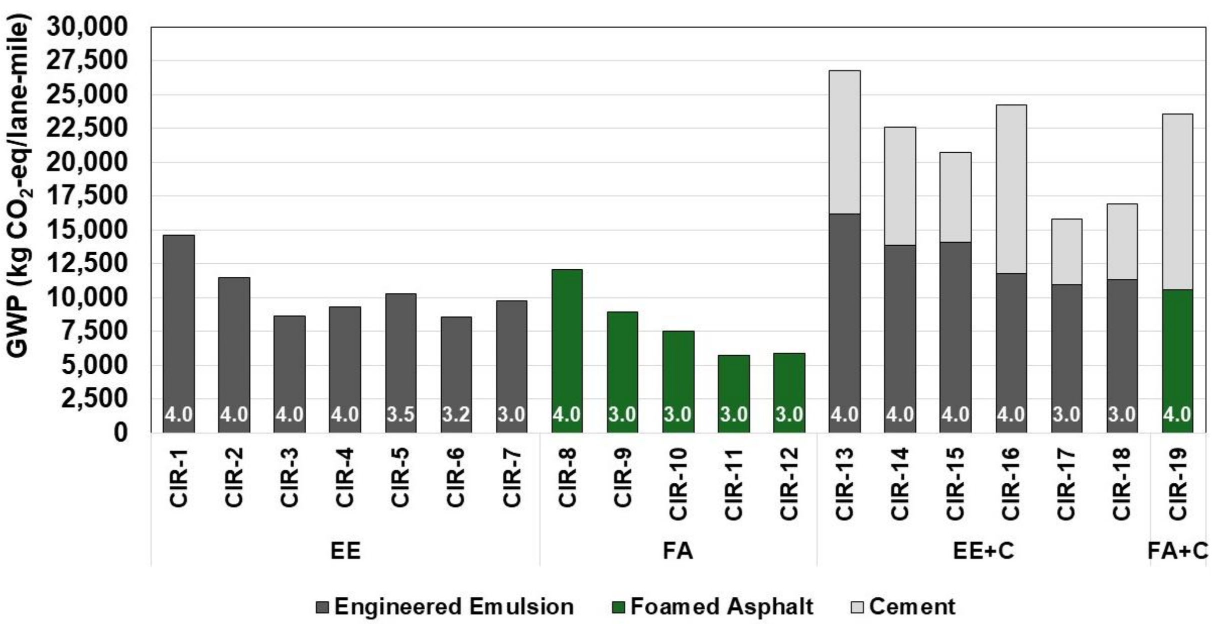
Project-Level GWP Results—Non-Virginia Cold In-Place Recycling Projects

The analysis of CIR projects highlights differences when compared with asphalt mixtures. For this study, all emissions related to the production of materials for the recycling operations were assigned to A1. Emissions from all recycling-related activities (application of recycling agent, mixing, and so on) were assigned to A3, and any paving and compaction equipment emissions were assigned to A5. Because the work is performed in situ, CIR was assumed to have no A4 (transport to the project site) component.

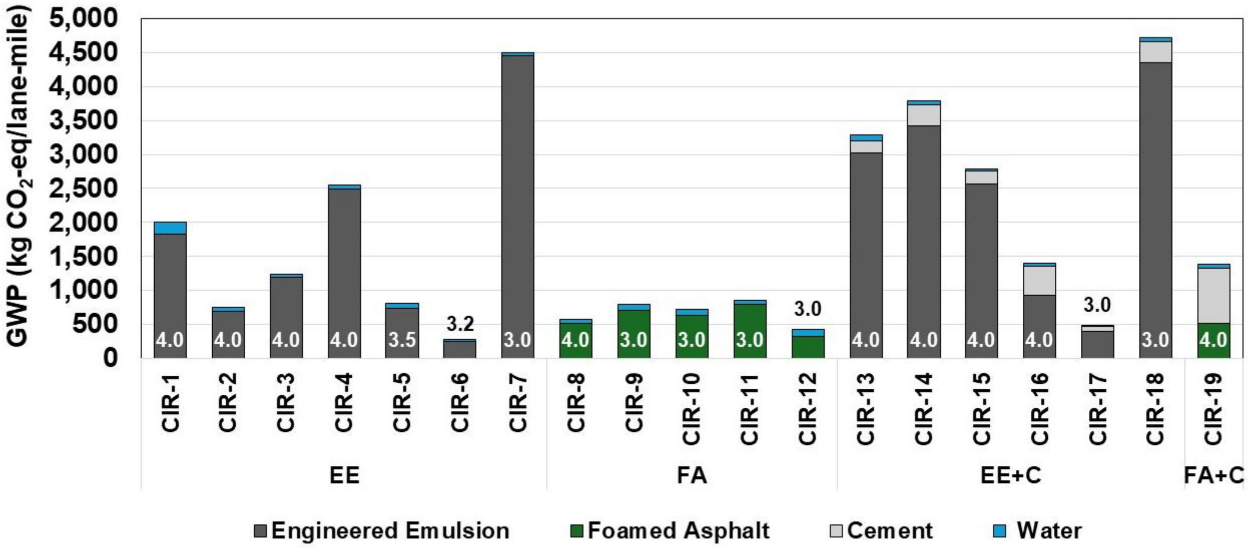
The detailed results for materials emissions (A1), shown in Figure 18a, indicate that cement has a large influence on A1. Figure 18b shows that some CIR projects using engineered emulsions (EE) tended to have higher transport emissions (A2) than those using foamed asphalt (FA). This difference was attributed to longer average haul distances for EE, likely due to the limited geographic availability of specialized emulsion suppliers. EE are often produced at centralized facilities, which increases emissions because of hauling. In contrast, FA is typically generated on site using standard binder and mobile recycling units, reducing the need for longer distance material transport.

CIR material production (A3), shown in Figure 18c, was dominated by emissions related to milling machine use, which accounted for approximately 76% of A3 emissions. Material crushers and pugmills followed, with approximately 18% of A3 emissions. Figure 18d shows the construction emissions (A5) subdivided by various construction equipment. The cold mix paver and double steel drum rollers contribute the highest emissions—approximately 45% and 33% of total A5 emissions, respectively.

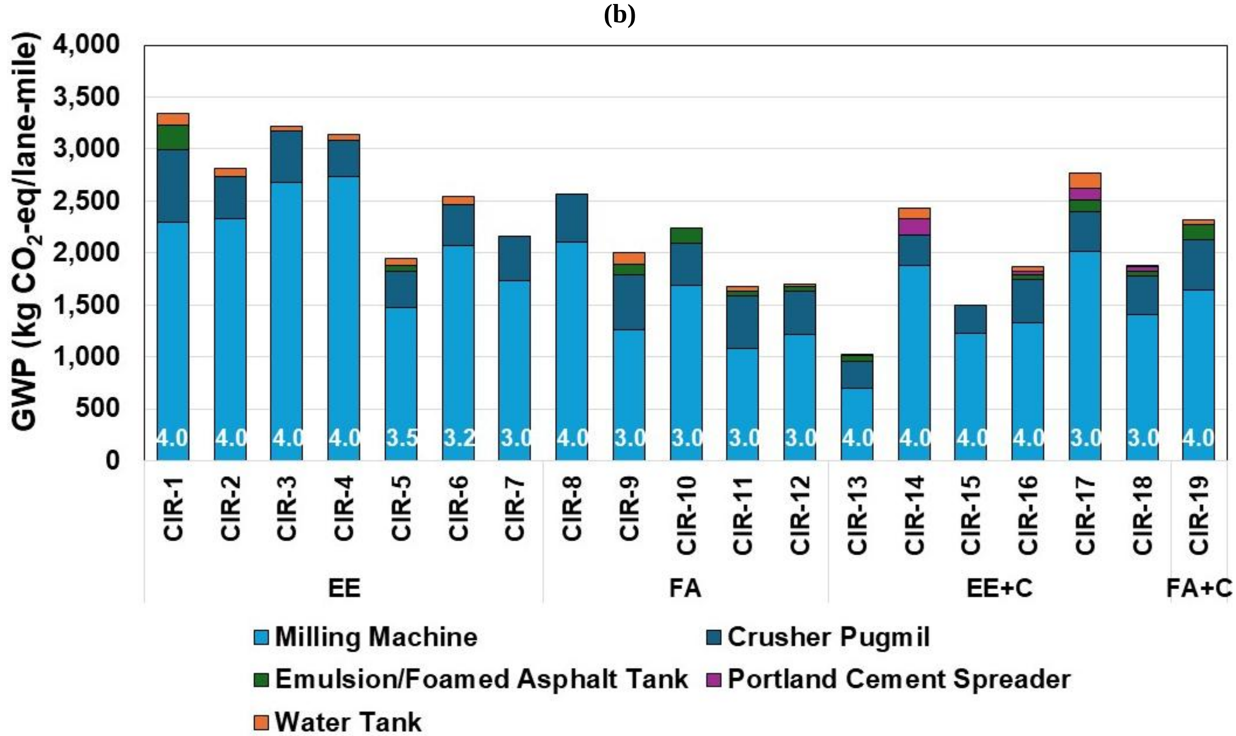
Total GWP values across these projects ranged from approximately 8,364 kg CO_2-eq to 31,408 kg CO_2-eq per lane-mile, reflecting variability in project scale, stabilizer type, and operational logistics (Figure 18e). Material extraction and production (A1) consistently accounted for the largest share of emissions across projects, with values ranging from around 5,732 kg to more than 26,789 kg CO_2-eq per lane-mile, reflecting the quantities of cement, emulsion, and foam asphalt used. Transport to production site emissions (A2) varied widely, with projects such as CIR-18 and CIR-7 reporting higher values due to longer haul distances and larger material quantities. Construction emissions (A5) ranged from approximately 1,330 kg to more than 4,249 kg CO_2-eq per lane-mile, driven by variations in equipment usage patterns, project lengths, and operational practices.



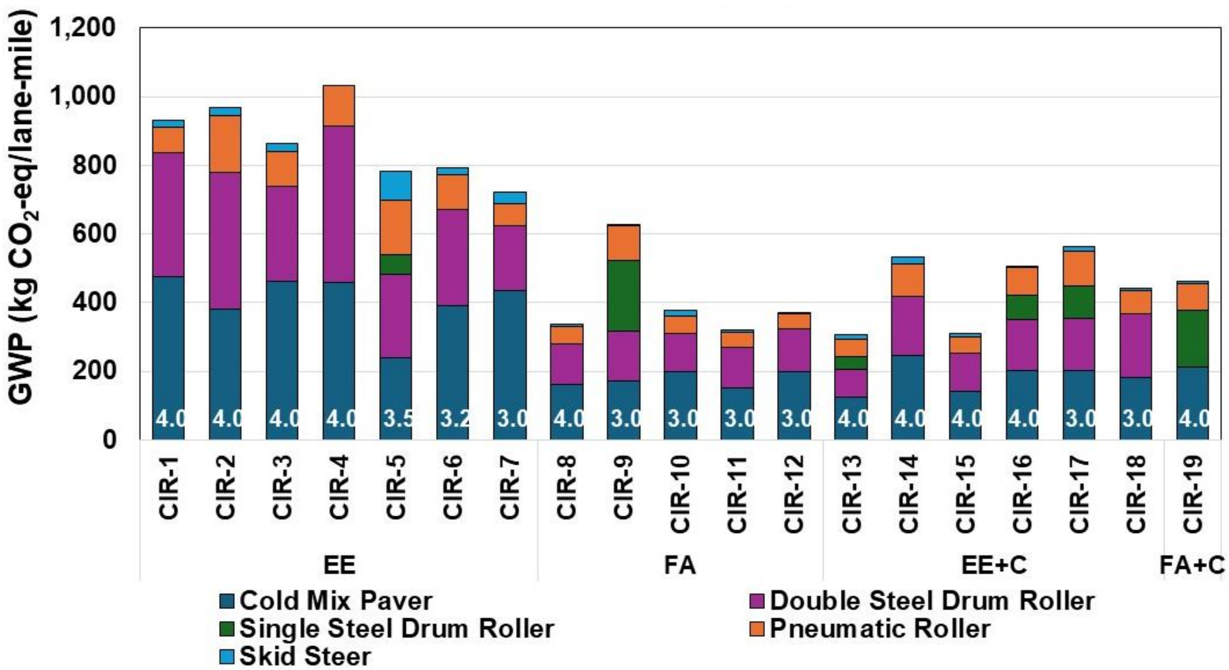
(a)


GWP (kg CO2-eq/lane-mile)
CIR-1
CIR-2
CIR-3
CIR-4
CIR-5
CIR-6
CIR-7
CIR-8
CIR-9
CIR-10
CIR-11
CIR-12
CIR-13
CIR-14
CIR-15
CIR-16
CIR-17
CIR-18
CIR-19
EE
FA
EE+C
FA+C
Engineered Emulsion
Foamed Asphalt
Cement
Water

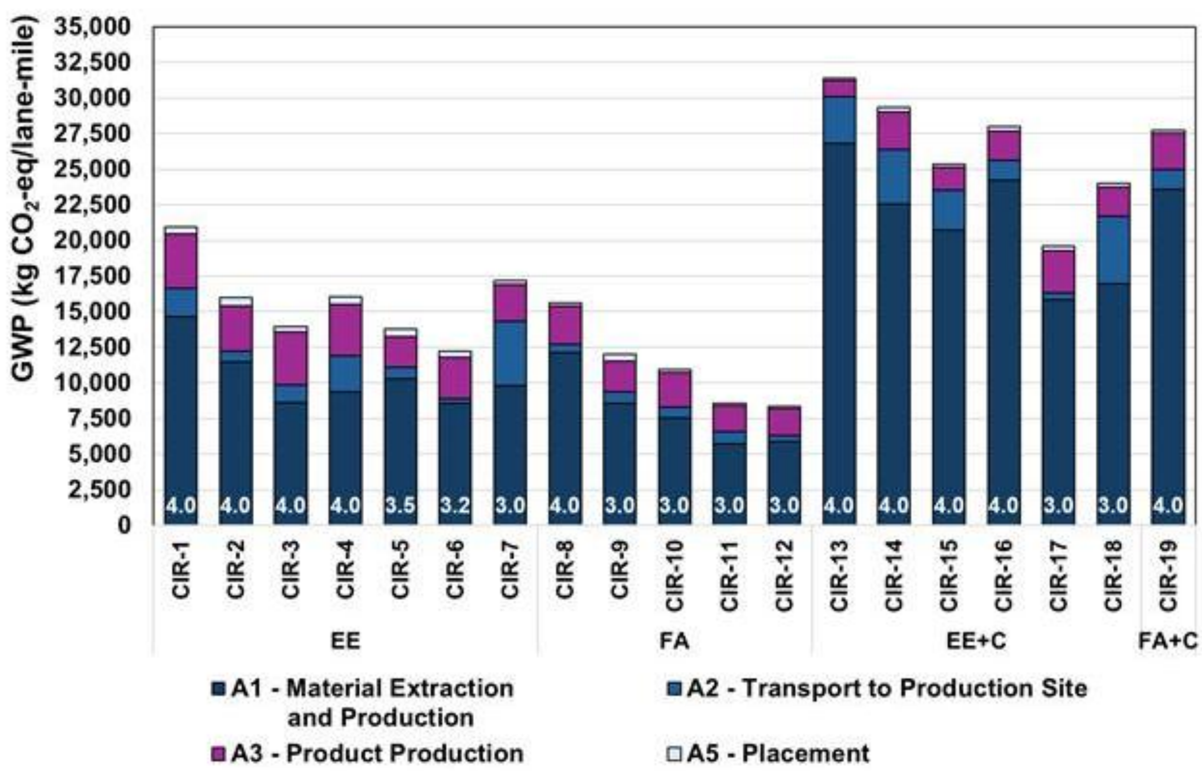
(b)


GWP (kg CO2-eq/lane-mile)
CIR-1
CIR-2
CIR-3
CIR-4
CIR-5
CIR-6
CIR-7
CIR-8
CIR-9
CIR-10
CIR-11
CIR-12
CIR-13
CIR-14
CIR-15
CIR-16
CIR-17
CIR-18
CIR-19
EE
FA
EE+C
FA+C
Milling Machine
Crusher Pugmil
Emulsion/Foamed Asphalt Tank
Portland Cement Spreader
Water Tank

(c)



(d)



(e)

Figure 18. Results for Cold In-Place Recycling Projects Showing Details of (a) A1-Material Extraction and Production; (b) A2-Transport to Production Site; (c) A3-Mixture Production; (d) A5-Construction; (e) Totals by Production and Construction Stage Modules. Thickness of recycled layer is highlighted in the base of each column. CIR = cold in-place recycling; EE = engineered emulsion; EE+C = engineered emulsion with cement as an active filler; FA = foamed asphalt; FA+C = foamed asphalt with cement as an active filler; GWP = global warming potential.

Projects utilizing only EE and FA as stabilizers generally showed lower total GWP values, whereas those incorporating cement as an active filler (EE+C, FA+C) recorded higher emissions, consistent with the known carbon intensity of cement production. For example, project CIR-13, which used engineered emulsion plus cement (EE+C), exhibited the highest total emissions at 31,408 kg CO_2-eq per lane-mile, whereas CIR-12 (FA) reported one of the lowest totals at 8,364 kg CO_2-eq per lane-mile.

Figure 19 shows the GWP results for the one FDR project assessed. Similar to the CIR projects, because the work is completed in situ, it was assumed that no A4 emissions (transport to project site) were present. Cement used for stabilization contributed approximately 130,288 kg CO_2-eq per lane-mile to materials extraction emissions (A1), accounting for most of total emissions across the project (Figure 19a). Transport emissions (A2) were relatively smaller, with cement and water transport contributing 999.6 kg CO_2-eq per lane-mile and 61.5 kg CO_2-eq per lane-mile, respectively (Figure 19b). This result suggests that although transport logistics are not negligible, they do not drive the carbon footprint of this process.

During production (A3), the reclaimer contributed about 1,626 kg CO_2-eq per lane-mile, amounting to approximately 65% of the total A3 emissions (Figure 19c). Support equipment, such as water trucks and cement spreaders, also contributed to A3 emissions, although their individual impacts were small compared with the reclaimer. Construction emissions (A5) related to equipment operations added a combined 895 kg CO_2-eq per lane-mile, with the padfoot roller contributing more than one-half (495.1.4 kg CO_2-eq per lane-mile) of A5 emissions (Figure 19d). Figure 19e shows total GWP for the FDR project—with a GWP profile dominated by materials emissions (A1).

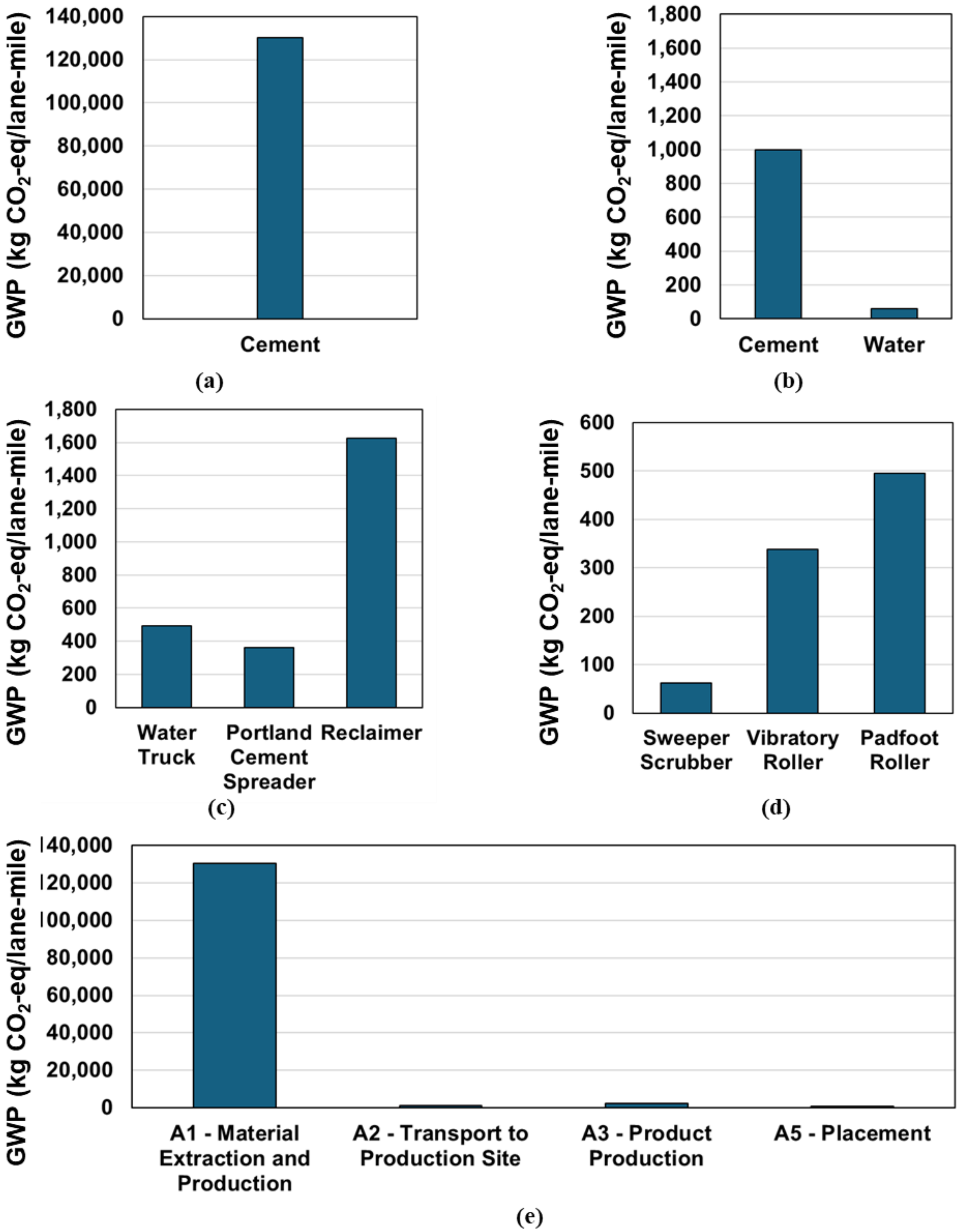


Figure 19. Results for Full-Depth Reclamation Showing Details of: (a) A1, Material Extraction and Production; (b) A2, Transport to Production Site; (c) A3, Mixture Production; (d) A5, Construction; (e) Totals by Production and Construction Stage Modules. GWP = global warming potential.

Proposed Roadmap

The following section outlines a potential path toward the implementation of sustainable pavement practices. The roadmap consists of six core pillars, each supporting a progressive shift in practice and capacity (Figure 20). These pillars were informed by lessons from the case studies, stakeholder input during the training symposium, and a review of national and international implementation models.

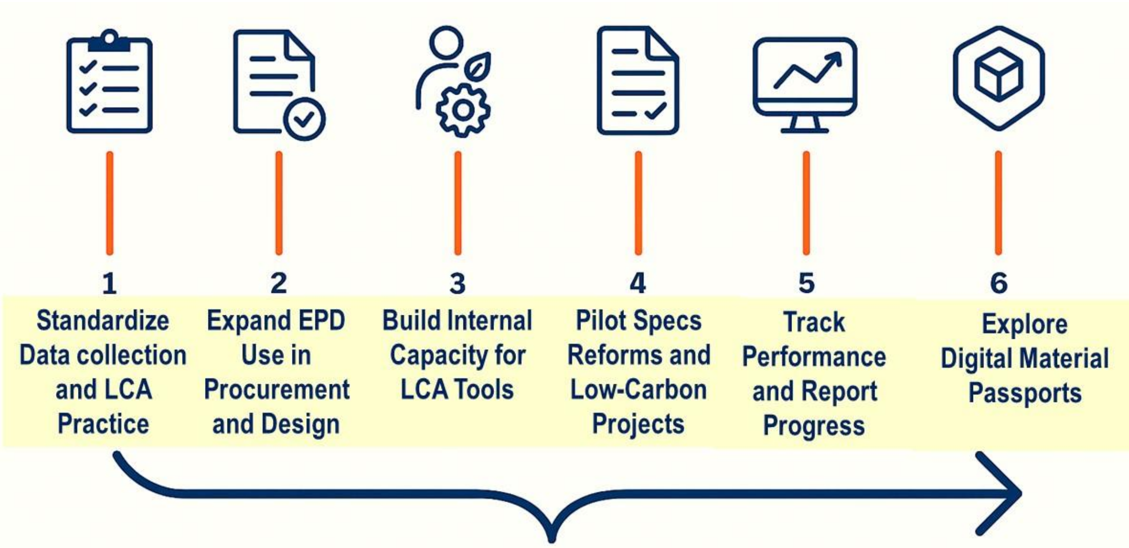


Figure 20. Proposed Agency Roadmap for Sustainable Pavement Practices. EPD = Environmental Product Declaration; LCA = life cycle assessment.

Standardize Data Collection and Life Cycle Assessment Practice

The first priority is to improve data availability and consistency for life cycle modeling. Although this study benefited from voluntary data collection efforts, future assessments will require more systematic and automated approaches. An agency should develop standardized data collection templates for contractors and suppliers, tied to pay items or project milestones. These forms should align with LCA input categories such as fuel consumption, material quantities, transport distances, and equipment use.

An agency should also consider establishing reporting protocols that facilitate integration with OpenLCA and FHWA's LCA Pave. Templates and guidance should be incorporated into project specifications and contract documents. In the longer term, integration of data loggers and digital construction management systems could automate the collection of high-resolution inputs needed for LCA.

Expand Environmental Product Declaration Use in Procurement and Design

Based on insights from the EPD evaluation, many agencies are well positioned to expand the use of EPDs in procurement decisions and project benchmarking. The agency can begin by encouraging or requiring EPD submission for certain asphalt mixture types or high-volume projects, particularly for which contractors already submit EPDs under the NAPA Emerald Eco-Label program.

EPDs can also be integrated into specification development and value engineering processes, particularly for projects that aim to meet "substantially lower" carbon thresholds. Over time, EPDs can inform adjustments to allowable mix designs, material sourcing strategies, and pavement layer configurations.

Build Internal Capacity for Life Cycle Assessment Tools and Decision-Making

The training conducted as part of this study served as a baseline effort to raise awareness of LCA and EPD tools. However, sustaining these practices will require deeper technical training and role-specific education. The roadmap recommends establishing an agency Sustainability and LCA Working Group comprising agency staff from relevant divisions and local university researchers. This group should meet periodically to evaluate case studies, share best practices, and support the development of LCA-based decision frameworks.

Pilot Specification Reforms and Low-Carbon Demonstration Projects

To test the integration of sustainability metrics into project delivery, an agency should initiate pilot projects that incorporate LCA findings and EPD thresholds into project selection criteria, bidding documents, and construction specifications. These pilot projects can be used to explore the trade-offs between cost, performance, and environmental impacts for different material strategies. Example methods might include exploring specification language for EPD submittals, developing acceptance criteria based on carbon intensity, and using performance incentives for low-emission materials. These efforts should be closely monitored, and the lessons learned should be used to inform broader specification revisions across the agency.

Track Performance and Report Progress

The roadmap calls for the development of a centralized sustainability performance dashboard that tracks emissions from low-carbon paving projects. This dashboard could be used to monitor progress toward climate goals, evaluate trends, and support transparency with the public and external stakeholders. The dashboard could be populated with metrics from EPDs, LCA models, and construction logs and should be updated periodically. Over time, the system could support scenario modeling, environmental budgeting, and integration with an agency's pavement management system.

Explore Digital Material Passports to Enhance Circularity and Transparency

As an agency moves toward more sustainable and climate-aligned infrastructure delivery, the use of digital material passports offers a forward-looking strategy to improve traceability and support circular economy goals. A material passport is a structured digital record that stores environmental, material, and performance data for construction materials, such as asphalt, concrete, steel, and recycled products throughout their life cycle.

By integrating material passports into procurement, design, and asset management systems, an agency could streamline access to data needed for LCA and benchmarking. This digital infrastructure could also facilitate material reuse, end-of-life decision-making, and documentation of low-carbon material choices. Integrating this concept with an agency's pavement management system or construction documentation platforms could support automated updates and data sharing among contractors, suppliers, and agency staff.

Summary of Findings

- Virginia asphalt mixtures were found to generally have lower GWP values than GSA's national benchmarks, based on submitted EPDs.

- Stone matrix asphalt mixtures had higher average GWP values compared with dense-graded asphalt mixtures. This outcome resulted from statistically significant differences in average emissions from material extraction and material transport to the production facility (A1 and A2, respectively).

- Surface asphalt mixtures had higher average GWP values compared with intermediate and base asphalt mixtures. This finding was derived from statistically significant differences in emissions from the material extraction (A1). The average GWP values showed no statistical difference when comparing intermediate and base asphalt mixtures.

- The average GWP showed no statistical difference when comparing HMA, HMA BMD, and WMA mixtures.

- Asphalt mixtures having 25 to 35% RAP contents had lower average GWP values compared with asphalt mixtures having 0 to 15% RAP. This outcome resulted from statistically significant differences in average emissions from material extraction and material transport to the production facility (A1 and A2, respectively).

- Asphalt mixtures having a larger NMAS (> 12.5mm) had lower average GWP values compared with asphalt mixtures having a smaller NMAS (< 12.5mm). This outcome was the result of statistically significant differences in material extraction (A1) emissions.

- Asphalt mixtures using polymer-modified binders had greater average GWP values than asphalt mixtures that did not use polymer-modified binders. This outcome resulted from statistically significant differences in emissions from the material extraction (A1).

- Regional differences in GWP values for asphalt mixtures were identified during this study, but a more complete picture will not be available until additional EPD data are submitted from all regions.

- Materials extraction emissions (A1) were the largest contributor to total GWP for the CIR projects studied.

- The presence of cement increased GWP for CIR projects using either engineered emulsion or foamed asphalt recycling agents.

- Fuel consumption for CIR projects was well correlated with recycled material quantities.

- The total GWP value for asphalt mixtures from the Virginia projects studied herein was dominated by material extraction and mixture production (A1 and A3, respectively). Construction emissions (A4 and A5) accounted for a relatively smaller share of total GWP.

- Materials extraction emissions (A1) were the primary component of total GWP for the FDR project studied.

CONCLUSIONS

- *The greatest proportion of emissions from the studied asphalt mixtures that are produced in Virginia comes from the materials extraction emissions (A1), followed by production emissions (A3).*

- *The greatest proportion of emissions from CIR projects completed outside of Virginia comes from materials extraction (A1). The presence of cement was a large contributor to A1 emissions, even though it was used at relatively low quantities.*

- *The greatest proportion of emissions from the FDR project completed in Virginia also came from materials extraction (A1).*

- *The proposed roadmap gives an example of how an agency could assess the effects of integrating sustainability into its pavement rehabilitation practices.*

RECOMMENDATION

1. *VTRC should share the information learned during this study to provide knowledge transfer on EPDs and LCA to VDOT staff.*

IMPLEMENTATION AND BENEFITS

The researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, VTRC will work with VDOT's Environmental, Materials, and Maintenance Divisions to develop a concluding workshop that can provide VDOT with additional training resources and knowledge transfer. This concluding workshop will be held by December 2026.

Benefits

Quantifying the emissions of its pavement rehabilitation decisions by LCA can help an agency make more informed decisions regarding environmental impacts.

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APPENDIX: LIFE CYCLE ASSESSMENT CASE STUDY EXAMPLE

Project Info - HMA			
Contractor	Chemung Contracting		
Date	9/12/2024	Mix Type	SMA 12.5A
District and County	Culpeper, Albemarle	Production Temp (°F)	335
Route Number	Rt 64	Plant Start Time	7:15 PM
Direction	Westbound	Plant End Time	3:00 AM
Project lane miles	1.89	Tons Produced	1256
Lane width	16		

Plant Inputs		
Energy Source	OFF-ROAD DIESEL USED (GALLONS)	RFO USED (Gallons)
Coal		
Natural Gas		
Electricity		
Fuel Oil	200	1672
Water		
Fuel Oil		
Other =		
Other =		

Source-to-Plant Transportation					
	Quantity	Vehicle used			One-way haul
Materials	(gals,ton)	Type	Capacity	Trips (#)	distance, miles
Aggregates (82.8 %)	1039.968	Off Road Haul Truck	40	26	0.75
Binder (5.9%)	74.104	Tanker - Morgan Oil	26	1	68
Filler (11.3 %)	141.928	Loader	4	35	0.08
Additives	0.02	N/A	N/A	0	0
Other =					
Other =					

(a)

Plant-to-Site Transportation					
Materials	Quantity (ton)	Vehicle used			One-way haul distance, miles
		Type	Capacity (tons)	# of trips	
Water					
Asphalt mix					
Additives					
Other =					

Site-to-Dump Transportation					
Operation	Quantity (ton)	Vehicle used			One-way haul distance, miles
		Type	Capacity (tons)	# of trips	
Milling	**756.00**	DUMP	18	42	16.1
Other =					

Construction					
Equipment	Make	Model	Vehicle Number	Fuel used	
				Type	Gallons
Paving					
Skid Steer	CAT	272D2	738	Diesel	
Vibratory Steel Drum Roller	CAT	CB13		Diesel	
Vibratory Steel Drum Roller	CAT	CB54	678	Diesel	
Vibratory Steel Drum Roller	CAT	CB36B	698	Diesel	
MTV	Weiler	E2850	1032	Diesel	
Paver	CAT	AP1055F	939	Diesel	
Tack Truck	International	T600	335	Diesel	
Water Truck	Sterling	TL9511	306	Diesel	
Milling					
Broom Tractor	Superior Broom	SM80CT	JSB1	Diesel	13.5
Skid Steer Broom	Deere	324G		Diesel	0
Water Truck	Ford	F650	JCW6	Diesel	25
Mill	Wirtgen	W210i	JML3	Diesel	237.5
Skid Steer	Bobcat	5740	JB5	Diesel	0
Other =					

(b)

Figure A1. Example Data Collection Form for HMA Paving Project: (a) Asphalt Mixture Production (A1–A3); (b) Construction (A4 and A5). HMA = hot mix asphalt; MTV = material transfer vehicle; N/A = not applicable; RFO = recycled fuel oil; SMA = stone matrix asphalt.