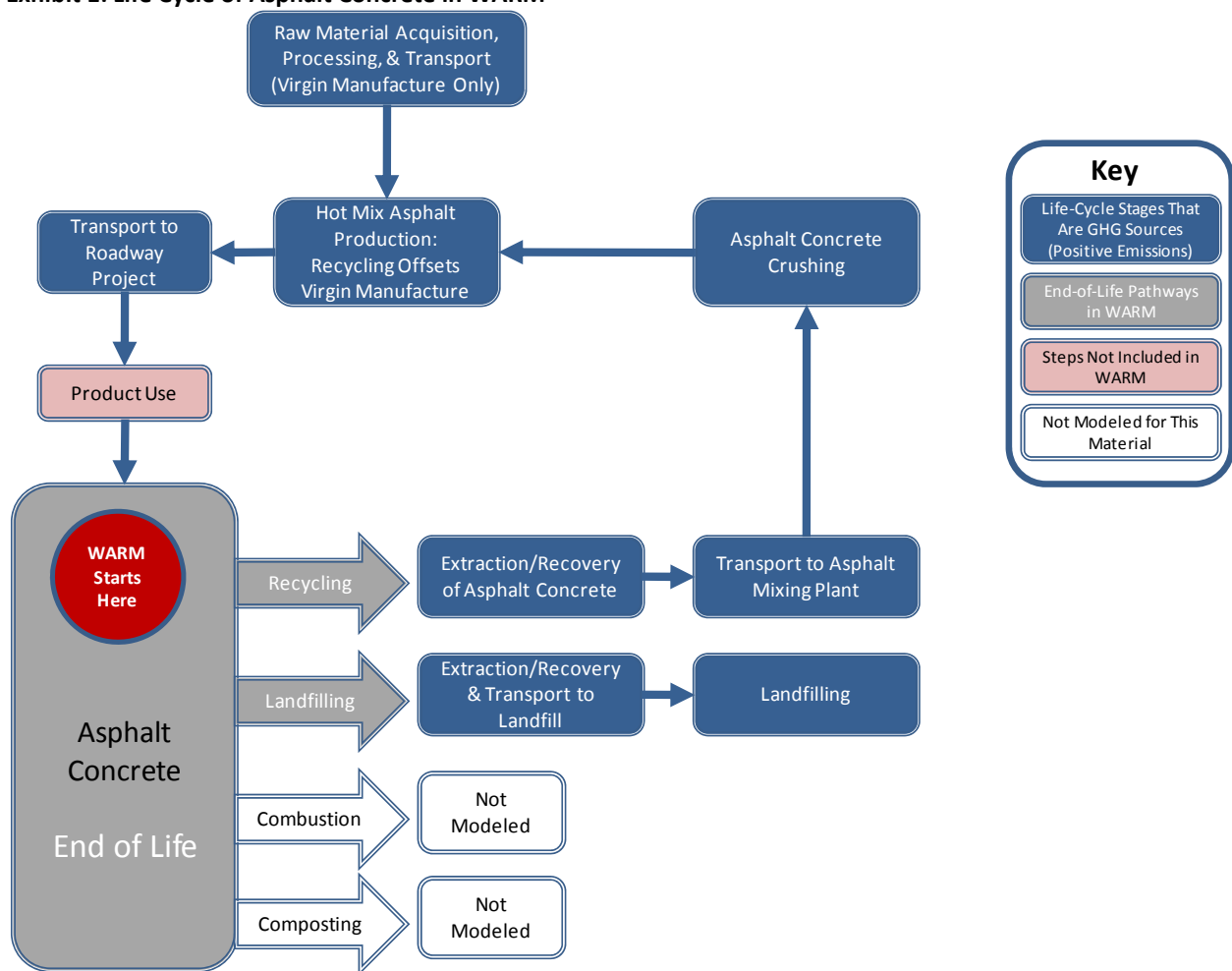


ASPHALT CONCRETE

1. INTRODUCTION TO WARM AND ASPHALT CONCRETE

This chapter describes the methodology used in EPA’s Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for asphalt concrete beginning at the waste generation reference point.¹ EPA uses the WARM GHG emission factors to compare the net emissions associated with asphalt concrete in the following three waste management alternatives: source reduction, recycling, and landfilling. Exhibit 1 shows the general outline of materials management pathways for asphalt concrete in WARM. For background information on the general purpose and function of WARM emission factors, see the [Introduction & Overview](#) chapter. For more information on [Source Reduction](#), [Recycling](#), and [Landfilling](#), see the chapters devoted to those processes.

Exhibit 1: Life Cycle of Asphalt Concrete in WARM



Asphalt concrete, commonly known as asphalt, is used in the construction of highways and roads. It is produced in a variety of mixtures, including hot mix, warm mix, cold mix, cut-back, mastic, and natural, each with distinct material and energy inputs. A highway or road is built in several layers,

¹ EPA would like to thank Dr. Marwa Hassan of Louisiana State University for her efforts at improving these estimates.

including pavement, base, and sub-base. The pavement layer, the surface layer, is made of either asphalt concrete or portland cement concrete.

Several different types of asphalt include road asphalt, hot mix asphalt, and concrete pavement. Hot mix asphalt (HMA) is the industry standard for production, with more than 94 percent of U.S. roads paved with HMA; therefore, EPA calculated the WARM GHG emission factors based on HMA life-cycle data.

2. LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The life-cycle boundaries in WARM start at the point of waste generation, or the moment a material is discarded, as the reference point and only consider upstream GHG emissions when the production of new materials is affected by material management decisions. Recycling and source reduction are the two materials management options that affect the upstream production of materials, and consequently, they are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on [Recycling](#) and [Source Reduction](#).

WARM does not consider composting or combustion for asphalt concrete. As Exhibit 2 illustrates, all of the GHG sources and sinks relevant to asphalt concrete in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life-cycle assessment.

Exhibit 2: Asphalt Concrete GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Asphalt Concrete	GHG Sources and Sinks Relevant to Asphalt Concrete		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	Offsets <ul style="list-style-type: none"> • Avoided process energy emissions, including aggregate production, asphalt binder production, combination of asphalt and binder • Avoided transportation for production of virgin crude oil • Avoided transportation of asphalt concrete materials to roadway project 	NA	NA
Recycling	Offsets <ul style="list-style-type: none"> • Avoided virgin material extraction • Avoided process energy for aggregate and asphalt binder production • Avoided virgin material transport (especially crude oil) 	NA	Emissions <ul style="list-style-type: none"> • Extraction/recovery • Transport to mixing plant • Crushing and remixing of asphalt concrete
Composting	Not applicable because asphalt concrete cannot be composted		
Combustion	Not modeled in WARM		
Landfilling	NA	NA	Emissions <ul style="list-style-type: none"> • Transport to construction and demolition landfill • Landfilling machinery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 2 and calculates net GHG emissions per short ton of asphalt concrete inputs. For more detailed methodology on emission factors, please see the following sections on individual waste management strategies. Exhibit 3 outlines the net GHG emissions for asphalt concrete under each materials management option.

Exhibit 3: Net Emissions for Asphalt Concrete under Each Materials Management Option (MTCO₂E/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Asphalt Concrete	-0.11	-0.08	NA	NA	0.04

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice. NA = Not applicable.

3. RAW MATERIALS ACQUISITION AND MANUFACTURING

For asphalt concrete, GHG emissions associated with RMAM are (1) GHG emissions from energy used during the raw materials acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.² Asphalt concrete is composed primarily of aggregate, which consists of hard, graduated fragments of sand, gravel, crushed stone, slag, rock dust, or powder and road-asphalt binder, a coproduct of petroleum refining (Exhibit 4). The process that energy GHG emissions result from is the manufacture of these main raw materials, plus the HMA production process. The production process involves sorting and drying the aggregate, heating the asphalt binder, and heating and applying the mixture. Aggregate material can be produced from numerous sources, including natural rock, reclaimed asphalt pavement (RAP), reclaimed concrete pavement (RCP), glass, fly ash, bottom ash, steel slag, recycled asphalt shingles, and crumb rubber. The transportation GHG emissions are generated from transportation associated with raw materials during manufacture and transportation to the roadway construction site. EPA assumes that non-energy process GHG emissions from making asphalt concrete are negligible because no data were available about non-energy emissions, and the majority of the asphalt concrete is aggregate, which has no non-energy emissions associated with its production.

Exhibit 4: Composition of Hot Mix Asphalt

Component	Hot Mix Asphalt Composition
Asphalt Binder	5.2%
Aggregate (Fine and Coarse)	94.8%

Source: Hassan 2009.

4. MATERIALS MANAGEMENT METHODOLOGIES

This analysis considers source reduction, recycling, and landfilling pathways for materials management of asphalt concrete.

Reclaimed asphalt pavement from HMA can be either recycled in an open loop as aggregate for a variety of materials or it can be recycled in a closed loop to produce new HMA, which results in lower input quantities of both new aggregate and new asphalt binder; WARM examines only the closed-loop pathway. An estimated 80–85 percent of waste HMA is recycled to produce aggregate or HMA (Levis, 2008). Asphalt concrete can also be landfilled in a construction and demolition (C&D) landfill. Descriptions of life-cycle energy and GHG emissions data for virgin asphalt mixture are available from

² Process non-energy GHG Emissions are emissions that occur during the manufacture of certain materials and are not associated with energy consumption.

the Athena Sustainable Materials Institute (Athena, 2001) and in a technical report published by Transportation Research Board (Hassan, 2009). This analysis considers source reduction, recycling, and landfilling for materials management of asphalt concrete.

Source reduction and recycling of asphalt concrete lead to reductions in GHG emissions because both strategies avoid energy-intensive manufacture of asphalt concrete from raw materials. Landfilling has a slightly positive emission factor resulting from the emissions from transportation to the landfill and operation of landfill equipment.

4.1 SOURCE REDUCTION

Virgin production of HMA is generalized to be a three-step process: (1) aggregate production, (2) road asphalt binder production, and (3) HMA production. Exhibit 5 summarizes the avoided emissions of source reducing virgin HMA. The avoided emissions associated with process energy and transportation energy are similar in magnitude, suggesting that the transportation of raw materials to the HMA plant and to the road site is as emissions-intensive as the actual production of the HMA itself. The following paragraphs give a further explanation of the process energy and transportation energy required for HMA production and avoided by source reduction. For more information on Source Reduction, please see the chapter on [Source Reduction](#).

Exhibit 5: Source Reduction Emission Factors for Asphalt Concrete (MTCO₂E/Short Ton)

Material/Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Sequestration for Current Mix of Inputs	Forest Carbon Sequestration for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Asphalt Concrete	-0.11	-0.11	NA	NA	-0.11	-0.11

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
 – = Zero emissions.

The GHG benefits of source reduction are calculated as the emissions savings from avoided raw materials acquisition and manufacturing (see Section 3) of asphalt concrete produced from a current mix of virgin and recycled inputs or from asphalt concrete produced from 100-percent virgin inputs. For asphalt concrete, the current mix is equivalent to the 100-percent virgin source reduction factor because asphalt concrete is not typically produced using recycled inputs.

Post-consumer emissions are the emissions associated with materials management pathways that could occur at end-of-life. No post-consumer emissions result from source reducing asphalt concrete because production of the material is avoided in the first place, and the avoided asphalt concrete never becomes post-consumer. Forest carbon storage is not applicable to asphalt concrete, and thus, does not contribute to the source reduction emission factor.

4.1.1 Developing the Emission Factor for Source Reduction of Asphalt Concrete

To calculate the avoided GHG emissions for asphalt concrete, EPA first looks at two components of GHG emissions from RMAM activities: (1) process energy and (2) transportation energy GHG emissions. No non-energy GHG emissions result from asphalt concrete RMAM activities. Exhibit 6 shows the results for each component and the total GHG emission factors for source reduction of asphalt concrete. More information on each component making up the final emission factor appears in Sections 4.2–4.5. A discussion of the methodology for estimating emissions from asphalt concrete manufactured from recycled materials can be found in the Recycling section.

Exhibit 6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Asphalt Concrete (MTCO₂E/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Asphalt concrete	-0.06	-0.05	–	-0.11

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.

– = Zero emissions.

Process energy includes the requirements to produce the raw material aggregate and asphalt binder to combine the aggregate and binder in an HMA plant and to produce the hot mix asphalt. By mass, most of the HMA is composed of aggregate and the remainder consists of asphalt binder (Exhibit 4). By far the most energy-intensive part of this process is the production of the asphalt binder. The HMA plant operations to produce the hot mix asphalt have more modest energy requirements, and the production of aggregate (extraction and processing of limestone, granite, and other stone) is even less energy intensive.

EPA obtained all data on the energy associated with the production of aggregate from the U.S. Census Bureau. EPA used the Fuels and Energy Report (Census Bureau, 1997) for data on the quantity of purchased fuels and electric energy consumed by the crushed stone industry based on North American Industry Classification System (NAICS). Also, EPA used the Mining-Subject Series Product Summary (Census Bureau, 2001) for data on the amount of crushed stone produced. Although the data are relevant to the late 1990s, this dataset represents the most updated information available from the U.S. Census.

EPA obtained energy inputs for the manufacturing process of asphalt binder from the Athena Sustainable Materials Institute’s Life Cycle Inventory for Road and Roofing Asphalt, prepared by Franklin Associates (Athena, 2001). For road asphalt binder production, we obtained data on virgin crude oil (which is a material input in manufacturing asphalt binder) from National Renewable Energy Laboratory’s (NREL) U.S. Life Cycle Inventory (LCI) Database (NREL, 2009). EPA also took data on limestone manufacturing from the U.S. LCI Database (NREL, 2009). Finally, we obtained energy inputs for the production of HMA from aggregate and asphalt binder from the Canadian Program for Energy Conservation (Natural Resources Canada, 2005). We then multiplied the fuel consumption estimates by the fuel-specific carbon contents. The process energy used to produce asphalt concrete and the resulting emissions appear in Exhibit 7.

Exhibit 7: Process Energy GHG Emissions Calculations for Virgin Production of Asphalt Concrete

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO ₂ E/Short Ton)
Asphalt concrete	0.95	0.06

EPA obtained transportation energy requirements for the asphalt binder, aggregate, and HMA from the Canadian Program for Energy Conservation (Natural Resources Canada, 2005). We assume the asphalt concrete materials are transported by truck, based on the average transport distance requirements for two different types of roadway projects: Class I Roadway (rural secondary highway) and Class II Roadway (urban arterial roadway). For the production of virgin crude oil, we obtained transportation data from NREL (2009). The U.S. LCI Database assumes no transportation is associated with the manufacturing of limestone. The transportation energy and the resulting emissions used to produce and deliver the asphalt concrete to the roadway project appear in Exhibit 8.

Exhibit 8: Transportation Energy Emissions Calculations for Virgin Production of

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO ₂ E/Short Ton)
Asphalt Concrete	0.73	0.05

Note: The transportation energy and emissions in this exhibit do not include retail transportation

4.2 RECYCLING

Asphalt concrete can be recycled into new HMA or aggregate, which can be used for several purposes. Both processes require the asphalt to be extracted and crushed before transportation to the mixing plant. EPA’s analysis focuses on the closed-loop recycling process, and does not consider the GHG benefits of recycling HMA into aggregate used for other purposes. For more information on Recycling, please see the chapter on Recycling.

The recycling of HMA into new HMA consists of transporting waste asphalt pavement to mixing plants, crushing it in RAP crushers, and mixing the resulting materials into new HMA. The waste pavement in this alternative replaces virgin natural aggregates, as well as asphalt binder.

To produce new HMA, the extracted asphalt concrete is transported to an HMA mixing plant, crushed, and mixed into new HMA. This process occurs at the mixing plant and uses the same energy inputs as HMA produced from virgin materials; therefore, energy savings for recycled HMA comes mainly from the avoided energy needed to obtain virgin materials (i.e., virgin aggregate) and to process the asphalt binder. Because the binder production represents the most energy-intensive part of the HMA production process, the greatest process-related savings from recycling HMA result from avoided binder production. The greatest overall savings from recycling result from the avoided transportation associated with virgin asphalt concrete manufacture, particularly because of the avoided transportation requirements for crude oil used as an input into asphalt binder production.

A recycled input credit is calculated for asphalt concrete by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the asphalt concrete from virgin inputs. GHG emissions associated with management (i.e., collection, transportation, and processing) of recycled asphalt concrete are included in the recycling credit calculation. Each component of the recycling emission factor as shown in Exhibit 9 is discussed in later paragraphs. For more information on recycling in general, see the Recycling chapter.

Exhibit 9: Recycling Emission Factor for Asphalt Concrete (MTCO₂E/Short Ton)

Material/Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit ^a Process Energy	Recycled Input Credit ^a – Transportation Energy	Recycled Input Credit ^a – Process Non-Energy	Forest Carbon Sequestration	Net Emissions (Post-Consumer)
Asphalt Concrete	–	–	-0.03	-0.05	–	NA	-0.08

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.

NA = Not applicable.

^a Includes emissions from the initial production of the material being managed.

– = Zero emissions.

4.2.1 Developing the Emission Factor for Recycling of Asphalt Concrete

EPA calculates the GHG benefits of recycling asphalt concrete by taking the difference between producing asphalt concrete from virgin inputs and producing asphalt concrete from recycled inputs, after accounting for losses that occur during the recycling process. This difference is called the “recycled input credit” and represents the net change in GHG emissions from process energy and transportation energy in recycling asphalt concrete relative to virgin production of asphalt concrete.

The recovery and processing of the recycled asphalt concrete require additional energy inputs. These inputs include the energy required to recover, load, and crush asphalt concrete (Levis, 2008); however, the GHG emissions associated with these additional energy inputs are outweighed by the GHG savings from the avoided raw material extraction for aggregate and crude oil, as well as the avoided asphalt binder production.

To calculate each component of the recycling emission factor, EPA uses the following four steps:

Step 1. Calculate GHG emissions from virgin production of one short ton of asphalt concrete. The GHG emissions from virgin production of asphalt concrete are provided in Exhibit 7 and Exhibit 8. EPA Calculates emissions from production of virgin asphalt concrete using the data sources and methodology also used to calculate the source reduction factor. EPA applies fuel-specific carbon coefficients to the process and transportation energy use data for virgin RMAM of asphalt concrete.

Step 2. Calculate GHG emissions from recycled production of asphalt concrete. Exhibit 10 and Exhibit 11 provide the process and transportation emissions associated with producing recycled asphalt concrete. The same amount of energy is required to remix HMA from recycled asphalt concrete as is required to produce HMA from virgin materials (Levis, 2008); therefore, the analysis uses data on virgin HMA production from the Canadian Program for Energy Conservation as described in the source reduction section (Natural Resources Canada, 2005).

Exhibit 10: Process Energy GHG Emissions Calculations for Recycled Production of Asphalt Concrete

Material/Product	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions (MTCO ₂ E/Short Ton)
Asphalt Concrete	0.41	0.03

EPA obtained transportation data for recycled asphalt concrete from Levis (2008). The transportation requirements include transporting the recovered asphalt concrete to the HMA mixing plant and then transporting the recycled HMA back to the road site. The largest energy benefit from recycling asphalt concrete is the avoided transport associated with the crude oil input used to produce the virgin asphalt binder.

Exhibit 11: Transportation Energy GHG Emissions Calculations for Recycled Production of Asphalt Concrete

Material/Product	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions (MTCO ₂ E/Short Ton)
Asphalt Concrete	0.05	0.00

Note: The transportation energy and emissions in this exhibit do not include retail transportation.

Step 3. Calculate the difference in emissions between virgin and recycled production. To calculate the GHG emissions implications of recycling one short ton of asphalt concrete, WARM subtracts the recycled product emissions (calculated in Step 2) from the virgin product emissions (calculated in Step 1) to calculate the GHG savings. These results appear in Exhibit 12.

Exhibit 12: Differences in Emissions between Recycled and Virgin Asphalt Concrete Manufacture (MTCO₂E/Short Ton)

Material/Product	Product Manufacture Using 100% Virgin Inputs (MTCO ₂ E/Short Ton)			Product Manufacture Using 100% Recycled Inputs (MTCO ₂ E/Short Ton)			Difference Between Recycled and Virgin Manufacture (MTCO ₂ E/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Asphalt Concrete	0.06	0.05	–	0.03	0.00	–	-0.03	-0.05	–

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
– = Zero emissions.

Step 4. *Adjust the emissions differences to account for recycling losses.* When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. Processors discard this portion in either the recovery stage or the remanufacturing stage; and consequently, less than one short ton of new material generally is made from one short ton of recovered material. Material losses are quantified and translated into loss rates. The recycled input credits calculated earlier are, therefore, adjusted to account for any loss of product during the recycling process. Because the recovered asphalt concrete is valuable and typically recovered on-site, the retention rate for recovered asphalt concrete is quite high. We assume, therefore, that the loss rates for recycling asphalt concrete are less than 1 percent by weight (Levis, 2008), and we assume that the recycling retention rate is 100 percent. Thus we do not adjust the GHG emissions associated with recycling (i.e., the difference between virgin and recycled manufacture), as shown in Exhibit 12.

4.3 COMPOSTING

Because of the nature of asphalt concrete components, asphalt concrete cannot be composted, and thus, WARM does not include an emission factor for the composting of asphalt concrete.

4.4 COMBUSTION

While asphalt concrete does contain combustible materials in the form of petroleum-based components, industry and academic experts indicate that asphalt is not combusted as an end-of-life management pathway, nor would it be logical to do so (Hassan 2009). The combustible components of asphalt concrete make up a relatively small percentage of the material (roughly 5 percent), meaning that a lot of energy would be wasted to heat up the non-combustible components at the facility (Levis, 2008). The uses for recycled asphalt also provide a more valuable end-use for the material than the value of energy recovery from combustion. Finally, emissions such as volatile organic compounds generated by combustion would provide emission control burdens at the facilities that outweigh the potential energy gains (Hassan, 2009). For these reasons, EPA does not include an emission factor in WARM for combustion of asphalt concrete.

4.5 LANDFILLING

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, since asphalt concrete does not contain bio-degradable carbon, there are zero emissions from landfill methane, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling asphalt concrete. Greenhouse gas emissions associated with RMAM are not included in WARM’s landfilling emission factors. As a result, the landfilling emission factor for asphalt concrete is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. Exhibit 13 provides the net emission factor for landfilling asphalt concrete. For more information on Landfilling, please see the chapter on [Landfilling](#).

Exhibit 13: Landfilling Emission Factor for Asphalt Concrete (MTCO₂E/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH ₄	Avoided CO ₂ Emissions from Energy Recovery	Landfill Carbon Sequestration	Net Emissions (Post- Consumer)
Asphalt Concrete	–	0.04	–	–	–	0.04

– = Zero emissions.

5. LIMITATIONS

As indicated in Section 1, asphalt concrete is produced in a variety of mixtures, including hot mix, warm mix, cold mix, cut-back, mastic, and natural, each with distinct material and energy inputs. EPA chose to analyze hot mix asphalt because of its widespread use in U.S. roadway projects. Recent studies indicate that warm mix asphalt may provide significant energy and GHG savings to the asphalt industry because of lower heat requirements during production (Hassan, 2009). As data become available, it will be important to estimate the life-cycle GHG emissions from the production and use of other types of asphalt concrete.

6. REFERENCES

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