Energy Usage and Greenhouse Gas Emissions of Pavement Preservation Processes for Asphalt Concrete Pavements

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INTRODUCTION

Construction, rehabilitation, and maintenance of highway pavements require obtaining, processing, transporting, manufacturing, and placement of large amounts of construction materials. These activities use substantial amounts of energy and generate greenhouse gasses (GHG). Differing philosophies have existed, and still exist, on the proper approach of managing, rehabilitating, and maintaining pavements. Methods range from one extreme of allowing the pavement to deteriorate and then reconstructing; to using preservation treatments to minimize effects of aging and maximize pavement life. Vastly different amounts of energy are consumed with different construction, rehabilitation, and preservation techniques. These various techniques also provide differing amounts of pavement design lives and life extensions. For each preservation treatment the life extension can be compared to the required energy and GHG emissions to determine an annualized energy use and GHG emission level. To minimize energy and GHG emissions over the life of the pavement, treatments can be chosen as having the lowest annualized energy use and GHG emissions.

1. ENERGY USE AND GHG EMISSIONS FOR CONSTRUCTION MATERIALS

When determining energy use and GHG emissions of various preventive maintenance treatments, the first issue is to determine the components of the process to measure. Some comparisons have been reported which only consider parts of the process, such as manufacturing or product placement. These comparisons can lead to misleading conclusions. A more accurate and realistic measure of energy use and GHG emissions of a specific type of work, is to begin with obtaining the raw materials from the earth and adding all the operation steps, such as transport, refining, manufacturing, mixing and placement.

Materials

Most materials used in asphalt pavement construction, rehabilitation, and maintenance processes consist of aggregates, of various gradations, and asphalt binders of different performance grades. The total energy used is obtained by starting with the raw material extraction and progressing to transportation and processing/refining.

Aggregates

Energy consumption for aggregate production includes the quarrying, hauling, crushing, and screening. Energy consumption for aggregate production ranges from 25,850 to 34,470 BTU/t (30 to 40 MJ/t), and GHG emissions range from 5 to 20 lb CO_2/t (2.5 to 10 kg CO_2/t).

Asphalt

Energy consumption for asphalt binder production includes crude oil extraction, transport, and refining. Energy consumption for asphalt binders has been determined to be 4.2 mmBTU/t (4900 MJ/t), and GHG emissions are 570 lb CO_2/t (285 kg CO_2/t). For asphalt emulsions, energy consumption is 3.0 mmBTU/t (3490 MJ/t) and GHG emissions are 442 lb CO_2/t (221 kg CO_2/t).

Manufacturing

Manufacturing includes all steps involved with handling, storing, drying, mixing, and preparation of materials for installation. Energy consumed varies depending on the specific material or product type. Typical manufacturing products for highway use include hot mix asphalt (HMA), cold mix, crack sealant, and drying surface dressing aggregate. Production of HMA consumes 237,000 BTU/t (275 MJ/t) and produces 44 lb CO_2/t (22 kg CO_2/t). Warm mix asphalt production consumes 201,000 BTU/t (234 MJ/t), approximately 15% less than HMA. Cold mix asphalt production only requires 12,000 BTU/t (14 MJ/t) because of not needing to heat the aggregate to elevated mixing temperatures.

Transport to Work Site

The produced construction materials must be transported to the work site. Energy consumed on transport varies with the distance and the quantity of material moved. Transport energy has been reported as 1,250 BTU/t-mile (0.9 MJ/km-t) with 0.2 lb CO_2/t-mile (0.06 kg CO_2/km-t).

Placement and Construction

Placement and construction consists of all activities required to install the materials or products. This includes traffic control, site and product preparation, compacting, finishing, clean up, waste disposal, etc. The highest energy consuming process for placement is hot in-place recycling (HIR) at 393,000 BTU/t (456 MJ/t) with 68 lb CO_2/t (34 kg CO_2/t) of GHG. This is due to the required heating to soften and reclaim the existing pavement. Placement of asphalt concrete and cold mixes require between 5,170 and 7,750 BTU/t (6 to 9 MJ/t) with 0.8 to 2.2 lb CO_2/t (0.4 to 1.1 kg CO_2/t) of GHG. Placement energy for PCC is the lowest at 1,900 BTU/t (2.2 MJ/t) with 0.4 lb CO_2/t (0.2 kg CO_2/t) of GHG.

Total Energy Use and GHG Emissions

Tables 2 and 3 are summaries of total energy use and GHG emissions for raw materials, manufacture, transport, and placement of various construction products (Chappat and Bilal, 2003). The data shows that PCCP use the highest energy consumption at app.860,000 BTU/t (1000MJ/t) .

Table 2: Total Energy Use for Pavement Construction Materials (Chappat and Bilal, 2003)

Energy Consumption (MJ/t) for Each Type of Product						
Product	**Binders**	**Aggregates**	**Manufacture**	**Transport**	**Laying**	**Total** (MJ/t)
Bituminous Concrete	279	38	275	79	9	**680**
Road Base Asphalt Concrete	196	36	275	75	9	**591**
High Modulus Asphalt Concrete	284	38	289	79	9	**699**
Warm Mix Asphalt Concrete	294	38	234	80	9	**654**
Emulsion Bound Aggregate	227	37	14	81	6	**365**
Cold Mix Asphalt	314	36	14	86	6	**457**
Cement-Bound Materials	200	32	14	67	6	**319**
Cement-Bound Materials & AJ	203	32	14	67	6	**323**
Aggregate w/Hydraulic Road Binder	50	29	14	61	6	**160**
Aggregate w/Hydraulic Road Binder & AJ	54	29	14	61	6	**164**
Cement Concrete Slabs without Dowels	598	40	14	84	2.2	**738**
Continuous Reinforced Concrete	1,100	29	14	81	2.2	**1,226**
Untreated Granular Material	0	40	-	68	6	**113**
Soil Treated In-situ w/Lime + Cement	63	0	-	7	12	**81**
Thermo-Recycling	98	4	-	12	456	**570**
Concrete Bituminous w/10% RAP	250	35	275	73	9	**642**
Road Base Asphalt Concrete w/20% RAP	157	33	275	64	9	**538**
Road Base Asphalt Concrete w/30% RAP	137	39	275	58	9	**510**
Road Base Asphalt Concrete w/50% RAP	98	25	275	47	9	**454**
Emulsion In-situ Recycling	105	4	-	15	15	**139**

Table 3: Total GHG Emissions for Pavement Construction Materials (Chappat and Bilal, 2003)

Greenhouse Gas Emissions (kg/t) for Each Type of Product						
Product	**Binders**	**Aggregates**	**Manufacture**	**Transport**	**Laying**	**Total** (kg/t)
Bituminous Concrete	16	9.4	22.0	5.3	0.6	**54**
Road Base Asphalt Concrete	11	7.6	22.0	5.3	0.6	**47**
High Modulus Asphalt Concrete	17	9.4	23.1	5.0	0.6	**55**
Warm Mix Asphalt Concrete	17	9.4	20.5	5.3	0.6	**53**
Emulsion Bound Aggregate	14	9.4	1.0	5.4	0.4	**30**
Cold Mix Asphalt	20	9.1	1.0	5.7	0.4	**36**
Cement-Bound Materials	39	5.7	1.0	4.5	0.4	**51**
Cement-Bound Materials & AJ	40	5.7	1.0	4.5	0.4	**51**
Aggregate w/Hydraulic Road Binder	10	5.1	1.0	4.1	0.4	**20**
Aggregate w/Hydraulic Road Binder & AJ	10	5.7	1.0	4.5	0.4	**22**
Cement Concrete Slabs without Dowels	118	9.6	1.0	5.6	0.2	**134**
Continuous Reinforced Concrete	188	5.1	1.0	5.4	0.2	**200**
Untreated Granular Material	0	9.6	-	4.5	0.4	**15**
Soil Treated In-situ w/Lime + Cement	12	-	-	0.5	1.1	**14**
Thermo-Recycling	6	1.0	-	0.8	34.2	**42**
Concrete Bituminous w/10% RAP	15	8.6	22.0	4.9	0.6	**51**
Road Base Asphalt Concrete w/20% RAP	9	7.8	22.0	4.3	0.6	**44**
Road Base Asphalt Concrete w/30% RAP	8	7.0	22.0	3.9	0.6	**41**
Road Base Asphalt Concrete w/50% RAP	6	5.2	22.0	3.1	0.6	**37**
Emulsion In-situ Recycling	7	1.0	1.1	1.0	0.4	**10**

2. ENERGY CONSUMPTION AND GHG EMISSIONS FOR CONSTRUCTION, REHABILITATION, AND PRESERVATION PROCESSES

Different types of pavement construction, rehabilitation, and preservation operations consume different amounts of energy. Energy use and GHG emissions per ton of product provide only a relative comparison of products. The specific pavement structure or work type together with the actual quantities of materials must be evaluated to more accurately compare energy use and GHG emissions for construction, rehabilitation and preservation. Dorchies (2008) performed several comparisons for different structured pavement sections, and determined that for different structures yielding the same structural performance, energy use and GHG emissions can vary as much as 80%.

For some pavement preservation treatments, including thin HMA overlays and HIR, energy use and GHG emissions are available. There have been some specific comparisons perfomed for various types of chip seals and for micro-surfacing. No references could be found for fog sealing and crack treatments. To provide uniform comparisons, the information developed by Chappat and Bilal (2003), from Tables 2 and 3 was used to calculate energy use and GHG emissions for typical preservation treatments. Energy use and GHG emissions were calculated per unit area of the pavement surface, using typical quantities of raw materials for each treatment. Preservation treatments considered include the HMA overlay, HIR, chip seal, micro-surfacing/slurry seal, crack fill, crack seal and fog seal. For some treatments, several different application rates of the treatment were considered. Table 4 shows calculated energy use and GHG emissions for these pavement preservation treatments. The analysis of energy use and GHG emissions considered the entire process for each treatment including raw materials, transport, processing, mixing and installation as appropriate. Further details on energy determinations are listed in the following discussions for each treatment type. For comparative purposes, Table 5 shows energy and GHG emissions for typical pavement construction and rehabilitation work types.

Table 4: Total Energy Use and GHG Emission for Pavement Preservation Treatments

TREATMENT	DETAILS	ENERGY USE		GHG EMISSIONS	
		BTU/yd^2	MJ/m^2	lb/yd^2	kg/m^2
Hot Mix Asphalt	Thickness 1.5" (3.8 cm)	46,300	59	9.0	4.9
	Thickness 2.0" (5.0 cm)	61,500	77	12.3	6.7
	Thickness 1.5" (3.8 cm) 50/50 Recycle/New	38,700	49	7.0	3.8

Hot In-place Recycling (HIR)	Thickness 2.0" (5.0 cm) 50/50 Recycle/New	51,300	65	9.0	4.9
Chip Seal	Emulsion 0.44 g/yd^2 (2.0 L/m^2) Aggregate 38 lb/yd^2 (21 kg/m^2)	7,030	8.9	0.9	0.5
	Emulsion 0.35 g/yd^2 (1.6 L/m^2) Aggregate 28 lb/yd^2 (15 kg/m^2)	5,130	6.5	0.7	0.4
Slurry Seal / Micro-surfacing	Type III, 12% Emulsion, 24 lb/yd^2 (13 kg/m^2)	5,130	6.5	0.6	0.3
	Type II, 14% Emulsion, 16 lb/yd^2 (8.7 kg/m^2)	3,870	4.9	0.4	0.2
Crack Seal	1 lin.ft./yd^2 (0.37m/m^2), 0.25 lb/ft (0.37 kg/m)	870	1.1	0.14	0.08
Crack Fill	2 lin.ft./ yd^2 (0.74 m/m^2), 0.50 lb/ft (0.74 kg/m)	1,860	2.0	0.25	0.14
Fog Seal	0.05 gal/yd^2 (0.23 L/m^2), 50/50 Diluted Emulsion	250	0.4	0.04	0.02
	0.10 gal/yd^2 (0.46 L/ m^2), 50/50 Diluted Emulsion	500	0.8	0.07	0.04
	0.15 gal/yd^2 (0.69 L/ m^2), 50/50 Diluted Emulsion	750	1.2	0.12	0.07

Table 5: Energy Use and GHG Emissions for Asphalt Concrete Pavement Construction and Rehabilitation

TREATMENT	DETAILS	ENERGY USE		GHG EMISSIONS	
		BTU/yd²	MJ/m²	lb/yd²	kg/m²
New Construction	4" (100 mm) HMA overlay 6" (150 mm) Aggregate Base[1]	156,820	198.5	24.1	13.1
Major Rehab Hot Mix Asphalt	4" (100 mm) Overlay [2]	112,800	142.8	20.9	11.3
	3" (75 mm) Overlay [2]	84,600	107.1	15.6	8.5
Major Rehab Warm Mix Asphalt	4" (100 mm) Overlay [2]	108,500	137.3	20.5	11.1
	3" (75 mm) Overlay [2]	81,400	103.0	15.3	8.3

1 Data from Dorchies (2005)
2 Data from Chappat and Bilal (2003)

Hot Mix Asphalt (HMA) Overlay

Thin HMA overlays, placed approximately 1.5 to 2.0 inches (3.8 to 5.0 cm) thick, are commonly used as a pavement preservation treatment. GHG data are calculated based on using a 140 lb/ft^3 (2240kg/m^3) in-place density. Results are shown in Table 7 for both a 1.5 and 2.0 inch (3.8-5.0 cm) thickness. The 1.5 inch (3.8 cm) thickness uses 0.079 t/yd^2 (86 kg/m^2) and the 2.0 inch (5.0 cm) thickness uses 0.105 t/yd^2 (114 kg/m^2). The analysis used an energy use of 586,000 BTU/t (680 MJ/t) for the entire process.

Hot In-Place Recycling (HIR)

HIR consists of heating, removing and remixing of one inch of the existing pavement surface followed by installation of a new one inch thick asphalt concrete overlay producing a two inch (5.0 cm) thick treatment. For comparison purposes a 1.5 inch (3.8 cm) total thickness is also shown. Energy use basis is 491,000 BTU/t (570 MJ/t).

Chip Seal

Two chip seal treatment designs were analyzed. First, a high quality design using 0.44 g/yd^2 (2.0 L/m^2) of asphalt emulsion with 38 lb/yd^2 (21 kg/m^2) of aggregate. The second design, a lesser binder application rate of 0.35 g/yd^2 (1.6 L/m^2) with a smaller aggregate gradation of 28 lb/yd^2 (15 kg/ m^2). Energy use is calculated including emulsion and aggregate raw materials, transport, and installation.

Slurry Seal/Micro Surfacing

Two slurry seal/micro-surfacing treatment designs were analyzed. First is a typical Type III aggregate, with 12% emulsion and a 24 lb/yd^2 (13 kg/m^2) application rate. The second design is a typical Type II aggregate, with a 14% emulsion and a 16 lb/yd^2 (8.7 kg/m^2) application rate. Energy use is calculated including emulsion and aggregate raw materials, transport, and installation.

Crack Seal

Crack sealing density is equivalent to one full length longitudinal crack per lane, and full width transverse cracks spaced at 36 feet (11.0 m). This crack pattern , for a typical lane mile produces 7,040 linear feet (2,146 m) of cracking for the area of 7,040 yd^2 (5,867 m^2) which is one linear ft/yd^2 (0.365 m/m^2). An installation rate of 5,000 pounds (2268 kg) per day is used. The application accounts producing an installation amount of sealant 0.25 lb/yd^2 (0.136 kg/ m^2). Energy use is calculated including raw materials, manufacturing, transport, field heating, reservoir cutting, and installation.

Crack Filling

Crack filling density is equivalent to a crack pattern of two full length longitudinal cracks, and full width transverse cracks spaced at 18 feet (5.5 m). This crack pattern, for a typical lane mile produces 14,080 linear feet (4,292 m) of cracking for the area of 7,040 yd^2 (5,867 m^2), which is 2 linear ft/ yd^2 (0.73m/m^2). An installation rate of 5,000 pounds (2268 kg) per day is used. The application accounts producing an installation amount of sealant 0.50 lb/yd^2 (0.272 kg/m^2). Energy is calculated including raw materials, manufacturing, transport, field heating, and installation.

Fog Seal

Fog sealing is calculated for three different application rates; 0.05, 0.10, and 0.15 g/yd^2 (0.23, 0.46, and 0.69 L/m^2) of a 50/50 water diluted asphalt emulsion. Energy use is calculated including raw materials, manufacturing, transport, and installation.

New Construction: Hot Mix Asphalt (HMA) Pavement

The structural section for the pavement is 4 inches (100mm) of HMA placed on 6 inches (150mm) of compacted aggregate base course. Energy is calculated including raw materials, heating, mixing, transport, placement, and compaction.

Rehabilitation: Hot Mix Asphalt (HMA) Pavement

Both a 4 inch (100 mm) thick HMA overlay and a 3 inch (75 mm) thick overlay were investigated. Energy is calculated including raw materials, heating, mixing, transport placement, and compaction.

Rehabilitation: Warm Mix Asphalt Pavement

Both a 4 inch (100mm) thick warm mix asphalt overlay and a 3 inch (75mm) thick overlay are examined. Energy is calculated including raw materials, heating, mixing, transport placement, and compaction.

3. ANNUALIZED ENERGY USE AND GHG EMISSIONS FOR CONSTRUCTION, REHABILITATION AND PRESERVATION PROCESSES

Pavement preservation treatments proactively address the pavement needs and are performed to prolong pavement life. There have been several studies that determined the amount of life extension provided by various pavement preservation treatments. The resulting life extensions have varied widely and are dependent on many factors including environmental factors, timing, treatment design, existing pavement distress, traffic levels, and quality of construction. The range of pavement life extensions for properly design and constructed preservation treatments are shown in Table 6. The energy and GHG data must be normalized for the expected pavement life extension to appropriately compare energy use and GHG emissions of preservation treatments. The normalization is accomplished by dividing unit area energy and GHG data from Table 4 by the life extensions in Table 6 to produce annualized results. The annualized results for pavement preservation treatments are shown in Table 7 and for new construction and rehabilitation work types in Table 8. In Table 7 the ranges for energy use and GHG emissions are due to the ranges of life extension times listed in Table 6.

Table 6: Pavement Life Extensions Provided by Pavement Preservation Treatments

TREATMENT TYPE	LIFE EXTENSION
Thin HMA Overlay	**5 – 10 years**
Hot In-Place Recycling	**5 – 10 years**
Chip Seal	**3 – 6 years**
Slurry/Micro Surfacing	**3 – 5 years**
Crack Sealing	**1 – 3 years**
Crack Filling	**1 – 2 years**
Fog Sealing	**1 year**

Table 7: Annualized Total Energy Use and GHG Emission for Pavement Preservation Treatments

Treatment	Details	Pavement Life Extension (years)	Energy Use per Year		GHG Emissions per Year	
			BTU/yd^2	MJ/m^2	lb/yd^2	kg/m^2
Hot Mix Asphalt	Thickness .5" (3.8 cm)	5 – 10	4,660 – 9,320	5.9 - 11.8	0.9 - 1.8	0.5 – 1.0
	Thickness 2.0" (5.0 cm)	5 – 10	6,080 - 12,160	7.7 - 15.4	1.2 - 2.4	0.7 – 1.3
Hot In-place Recycling	Thickness 1.5" (3.8 cm) 50/50 Recycle/New	5 – 10	3,870 – 7,740	4.9 - 9.8	0.7 - 1.4	0.4 – 0.8
	Thickness 2.0" (5.0 cm) 50/50 Recycle/New	5 – 10	5,130 - 10,260	6.5 - 13.0	0.9 - 1.5	0.5 - 1.0
Chip Seal	Emulsion 1.6-2.0 L/m^2 Aggregate 15-21 kg/m^2	2 – 6	1,026- 2,565	1.3 - 3.3	0.14 - 0.35	0.08 - 0.2
Slurry Seal / Micro-surfacing	Type III, II 12-14% Emulsion, 24 lb/yd^2	2 – 5	968- 1,9350	1.2-2.4	0.10 - 0.2	0.05 - 0.10
Crack Seal	1 lin.ft./ yd^2 (0.37m/m^2), 0.25 lb/ft (0.37 kg/m)	1 – 3	290 - 870	0.4 - 1.1	0.05 - 0.14	0.03 - 0.08
Crack Fill	2 lin.ft./ yd^2 (0.74 m/m^2), 0.50 lb/ft (0.74 kg/m)	1 – 2	930 - 1,860	1.0 - 2.0	0.13 - 0.25	0.07 - 0.14
Fog Seal	0.23 -0.46-0.69 L/m^2 50/50 Diluted Emulsion	1	250-750	0.4-1.2	0.04-0.12	0.02- 0.07

Table 8: Annualized Energy Use and GHG Emissions for Asphalt Concrete Pavement Construction and Rehabilitation

Treatment	Details	Design Life (years)	Energy Use per Year		GHG Emissions per Year	
			BTU/yd^2	MJ/m^2	lb/yd^2	kg/m^2
New Construction	4” (100 mm) HMA over 6” (150 mm) Aggregate Base	20	7840	9.9	1.2	0.7
Major Rehab Hot Mix Asphalt	4” (100 mm) Overlay	15	7500	9.4	1.3	0.8
	3” (75 mm) Overlay	12	7050	8.9	1.3	0.7
Major Rehab Warm Mix Asphalt	4” (100 mm) Overlay	15	7210	9.2	1.3	0.8
	3” (75 mm) Overlay	17	6780	8.5	1.3	0.7

The results group into three categories.

The first category includes the thin HMA overlay, HIR, new construction, and rehabilitation, have the highest annualized results ranging from 3,870 to 12,160 BTU/yd^2-yr (4.9-15.4 MJ/yd^2-yr) energy and 0.9 to 2.4 lb/yd^2-yr (0.4-1.3 kg/m^2-yr) of GHG.

The second category includes chip seal, micro-surface, and crack fill at 930 to 2,565 BTU/yd^2-yr (1.0-3.3 MJ/yd^2-yr) energy and 0.13 to 0.35 lb/yd^2-yr (0.07-0.20 kg/m^2-yr) of GHG.

The third and final category includes fog sealing and crack sealing with 250 to 870 BTU/yd^2-yr (0.4-1.1 MJ/m^2-yr) energy and 0.04 to 0.14 lb/yd^2-yr (0.02-0.08 kg/m^2-yr) of GHG.

The annualized energy and GHG emission results in Table 7 show that the different pavement preservation treatments provide a year of life extension with differing energy requirements and GHG emissions. Each type of pavement treatment will not always be appropriate for all pavements, distresses, traffic, climate, desired results, etc.

CONCLUSIONS

Comparisons of energy use and GHG emissions for the construction, rehabilitation and preservation of asphalt concrete pavements are calculated and compared. Results show that on an annualized basis, different process types require differing amounts of energy per year of pavement life. New construction, major rehabilitation, thin HMA overlay, and HIR have the highest energy use and range from 5,000 to 10,000 BTU/yd^2-yr (6.3-12.6 MJ/m^2-yr). Chip seals, slurry seals, micro-surfacing, and crack filling utilize lower amounts of energy per year of extended pavement life and range from 1,000 to 2,500 BTU/yd^2-yr (1.3-3.3 MJ/m^2-yr). Crack seals and fog seals use the least amount of energy per year of extended pavement life at less than 1,000 BTU/yd^2-yr (1.3MJ/m^2-yr).

Energy use and GHG emissions for the different products depend primarily on the type and quantity of materials placed per unit area. Products that use lower amounts of asphalt per unit area and products that do not require heating of aggregate use the least amounts of energy. Additionally, products having the lowest quantity of material applied to the pavement per unit area utilize less energy, simply because not as much material needs to be produced, processed, transported and installed. To minimize energy use and GHG emissions over the life of a pavement, all preservation treatments should be utilized as appropriate to the maximum extent possible for the existing pavement conditions.