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Life-Cycle Environmental and Economic Assessment of Using Recycled Materials for Asphalt Pavements

Technical Report
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Abstract

The public, industry and governments have become increasingly interested in green design and engineering as approaches towards better environmental quality and sustainable development. Pavement construction is one of the largest consumers of natural resources. Recycling of pavements represents an important opportunity to save the mining and use of virgin materials, conserve energy, divert materials away from landfills, and save scarce tax dollars. How much pollution, energy, natural resources, and money could be saved by using secondary materials in road construction? What are the engineering limits of using recycled materials in roads? Can we recycle over and over again pavements that contain rubber, glass, and other secondary materials? This research will quantify the environmental and economic costs and benefits of recycling asphalt pavements, and using secondary materials for their construction. The impacts will be traced through the related life-cycles and supply chains for material and energy inputs, water consumption, hazardous and non-hazardous waste generation, toxic discharges, and greenhouse gas as well as particulate matter emissions. Life-cycle environmental and economic assessment methods will be coupled with construction process models. Stakeholders will be able to use the resulting computer tool for decision-making and scenario analysis as parameters of the pavement recycling model change over time and from region to region.

Key words: pavement management, life cycle costs, environmental costs, pavement recycling

Introduction

The construction of pavements requires a significant amount of non-renewable materials and energy. The sheer size of the energy and material investments dictates that a better understanding of the environmental and economic aspects of the use of virgin versus recycled materials might lead to a more sustainable future for the asphalt construction sector. If clear benefits such as the diversion of materials from landfills exist, other benefits depend on a set of specific characteristics and the indicators used to judge the performance of construction activities. Both processing and transportation are important to the balance between costs and benefits of recycling.

This report starts with an analysis of various materials and their potential use in pavement construction. Economic, environmental, and engineering characteristics and constraints are discussed next. Finally, a tool (PaLATE) to assess environmental and economic impacts of the use of different materials and recycling for the construction and maintenance of pavements is introduced and described.

1) The Potential Use of Recycled Materials for Asphalt Pavements

Recycled materials of interest to pavement construction are obtained from the demolition of civil engineering structures, and waste materials from industry. Alternatively, such materials would be disposed in a landfill. Recycled materials used in construction may be classified according to their source [Pihl 2003]:

1. Industrial byproducts, such as steel slag, and coal fly ash.
2. Road byproducts, such as reclaimed concrete pavement materials, and reclaimed asphalt pavement materials.
3. Demolition byproducts, such as crushed concrete, tiles, and bricks.

The incorporation of recycled materials in road construction and the substitution for virgin materials is perceived as an opportunity to save resources and avoid the impacts associated with their extraction and transportation. The use of byproducts in road construction is important to divert loads that would be otherwise disposed of in landfills. A significant range of applications of different recycled materials in road construction has been identified that has the potential to accomplish such goals (Table 1).

A report [Nehdi 2001] identified 43 types of secondary materials used in road construction out of which 11 are industrial byproducts, and 7 come from the metallurgic industry. The annual production of foundry byproducts in the U.S. corresponds to 15 million tons [Naik 2002]. Worldwide, 20 million tons of granulated blast furnace slags and 2 million tons of silica fume are annually produced [Malhotra 1999]. In 1989, the U.S. produced 130,000 tons of condensed silica fumes [Malhotra 1993].

	APPLICATIONS					
MATERIALS	Asphalt Concrete	Portland Cement Concrete	Stabilized Base	Flowable Fill	Granular Base	Embankment Fill
Baghouse Fines	✓					
Blast Furnace Slag	✓	✓			✓	
Coal Bottom Ash/Slag	✓		✓		✓	
Coal Fly Ash	✓	✓	✓	✓		✓
Flue Gas Scrubber Material						
Foundry Sands	✓			✓		
Kiln Dusts	✓		✓	✓		
Mineral Processing Wastes	✓				✓	✓
Municipal Combustor Ash	✓				✓	
Nonferrous Slags	✓				✓	✓
Quarry Byproducts				✓		
Reclaimed Asphalt Pavement	✓				✓	✓
Reclaimed Concrete Pavement		✓			✓	✓
Roofing Shingle Scrap	✓					
Scrap Tires	✓					✓
Sewage Sludge Ash	✓					
Steel Slag	✓				✓	
Sulfate Wastes			✓			
Waste Glass	✓				✓	

Table 1: Byproducts and Their Application in Road Construction [Chesner 2003]

The annual production of consumer wastes and industrial byproducts in the U.S. that could be recycled amounts to more than 4.5 billion tons [Naik 2002]. One prominent byproduct that is used in construction is fly ash. Annually 450 million tons of fly ash are produced worldwide, but less than 8% are used to produce cement. The annual output in the U.S. corresponds to 48 million tons, and the domestic consumption of dry, stored fly ash is approximately 41% of that [Misra 2003].

a) Economic Aspects

The diversion of materials from landfills can be translated into economic benefits because of the avoided tipping fees charged to dump material in landfills. A table with average tipping fees for various states in the U.S is presented in Appendix 1. If a $37/ton average tipping fee for landfills in the U.S. is assumed [Biocycle 2002], the marginal benefit of recycling one ton of road construction materials is more than $41, excluding processing and transportation costs, but including the avoided cost of virgin materials. Table 2 shows the 1997 amounts of non-renewable construction materials used in the U.S., costs per ton, and the total expenditures by material type.

Resource	**Average Price in 1997**	**Application**	**Amount Used in 1997 (10^6 tons)**	**Total Expenditures in 1997**
Crushed and broken limestone and dolomite	$4.16/ton	Asphaltic concrete	4.08	$16,972,800
		Road construction resurfacing	28.68	$119,308,800
Sand	$4.26/ton	Asphaltic concrete	4.14	$17,636,400
		Road construction resurfacing	7.34	$31,268,400
Gravel	$4.26/ton	Asphaltic concrete	3.00	$12,780,000
		Road construction resurfacing	10.06	$42,855,600
Crushed sandstone	$14.50/ton	Aggregate	0.32	$4,640,000
		Construction	0.24	$3,480,000
Clay	$5.74/ton	Construction	0.05	$287,000

Table 2: Consumption of Mined Natural Resources by Highway Construction and Other Construction Related Activities [Butalia 2001].

A dynamic assessment of the price evolution for sand and gravel highlights the future importance of recycling as a cost saving measure. Figure 1 shows the producer price index for construction sand and gravel.

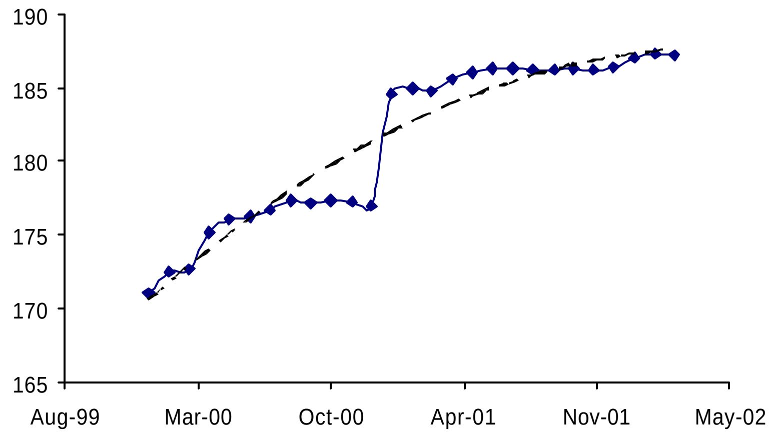

Figure 1: Producer Price Index for Construction Sand and Gravel (June 1986 = 100) [BLS 2003]

A partial evaluation of the revenues from recycling of road construction materials is straightforward; however, a more thorough assessment is needed for a comprehensive cost-benefit analysis. One clear advantage is the reduction on the demand for space in landfills, but other benefits are not so easy to quantify. Depending on the circumstances and the indicators used in the assessment, recycling may actually be economically (and environmentally) detrimental. The proximity of recycled materials to the construction site may be translated into less transportation expenses and fuel consumption, but overall cost and energy savings depend on a broader picture of recycling. For example, cement manufacturing in the U.S. costs $100/ton, whereas the cost of fly ash can reach $90/ton [Malhotra 1993]. In this case the difference is not that significant, and hauling costs may even out the costs.

Nonetheless, some authors argue that the use of recycled materials has economic and environmental benefits [Masood 2001]. In Canada, the use of high-volume fly ash with 5 kg/m^3 of superplasticizers (concrete additives) saves $12 compared with the cost of plain Portland cement concrete [Malhotra 1999]. In Ohio 10 million tons of coal combustion products (CCP) are generated per year. About 20% is used in concrete and asphalt mixes, embankments, structural fills, stabilized base, subbase, and flowable fills [Butalia 2003]. The Ohio Department of Transportation estimates that potential savings associated with the use of recycled materials correspond to $37 million.

b) Engineering Constraints

Even if the economic assessment is favorable some physical properties of the materials and technical requirements established by the transportation agencies may limit the use of recycled materials. If a material fulfills the technical requirements but the life-time of the structure is reduced due to its use, a life-cycle cost analysis can determine whether the use of virgin or recycled material is more advantageous. Similarly to other construction materials, the feasibility of using alternative materials is based on a set of physical properties [Soeda 2001]:

- compressive strength
- bulk density
- moisture content
- specific gravity
- setting time
- shrinkage or expansion
- tensile strength
- flexural strength
- hydraulic conductivity
- porosity

For example, the engineering properties of fly ash, which are the most effective for its performance in flowable fill mixtures[1] are its spherical particle shape and pozzolanic characteristics. Some of the engineering properties of flowable fill mixes containing fly ash that are of particular interest when fly ash is used as a principal component in flowable fill mixes include compressive strength, flowability, stability, bearing capacity, modulus of

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[1] Flowable fill is defined by the American Concrete Institute as "a self-compacting cementitious material that is in a flowable condition at time of placement, and has a compressive strength of 1200 psi or less at 28 days. Most flowable mixes are designed to have strengths of 150-200 psi for ease of excavation at a later time." Typically it consists of a mixture of fine aggregate or filler, cementitious material, and water." A flowable fill is self-leveling, does not need compaction, hardens in a couple of hours after placement, and can be placed in freezing temperatures [Butalia 2001].

subgrade reaction, time of set, bleeding and shrinkage, density, and permeability. Various characteristics of fly ash are presented in detail in Appendix 2, and the advantages and disadvantages of fly ash used in structural fills and embankments are shown in Table 3.

Advantages	Disadvantages
• readily compacted by standard construction equipment over a wide range of water contents; • easily handled due to light weight and uniform, fine-grained particle size; • high shear strength creates stable embankments; • low unit weight reduces transportation costs and is useful for sites with poor foundation soils; • rapid consolidation results in low settlements after construction; • often available in urban areas where other borrow sources *may* be scarce, and • moisture content often adjustable at source for ease of use in wet weather or for drying saturated site soils.	• easily eroded internally and externally by water, resulting in gullies and piping; • easily dried and eroded by wind causing dusting; • fine-grained and abrasive to construction equipment, especially dozers and other tracked vehicles; • susceptible to liquefaction if saturated; • potentially susceptible to frost heave, if saturated, and • unfamiliarity may result in resistance from regulators, contractors, and the public.

Table 3: Summary of the Advantages and Disadvantages of Fly Ash Used in Structural Fills and Embankments [DiGioia Jr. 2003].

While fly ash produced better, more durable and less permeable concrete when it reaches its full strength, fly ash content slows down initial concrete curing.

Another industrial byproduct that is used in highway construction is foundry sand. Silica sand coated with a thin film of burnt carbon, residual binder (bentonite, resins) and dust are the main constituents of used foundry sand. Since silica sand is hydrophilic, it attracts water to its surface. This property could lead to moisture-accelerated damage and associated stripping problems in an asphalt pavement. Antistripping additives may be required to counteract such problems [Johnson 1981].

c) Environmental Constraints

The environmental concerns about the use of recycled materials include a potential for certain constituents to leach into the soil and groundwater at concentrations that can be hazardous to human health and the environment, and the environmental effects of processing and transporting secondary materials.

The use of byproducts needs to be assessed in terms of their potential environmental consequences and how they compare to the materials they are substituting. Table 4 shows the average metal leachate concentrations in µg/Liter for various construction materials, and how these values compare to the ones established by the Texas Risk Reduction Program (TRRP).

Metal	TRRP Limits in Texas	Cement	Fly Ash	RAP	RCP (RCM)	Bottom Ash	Siliceous Gravel	Siliceous Sand	Sandstone	Limestone
Al	24000	2000	12520	2000	2000	4800	2000	2000	2000	2000
Sb	6	5.73	15.43	5.74	5.42	5.14	6.71	13.03	6.26	7.5
As	50	25	27.95	25	25	25	25	25	25	25
Ba	2000	3555	2224	2007	2000	2000	2007	2000	2000	2000
Be	4	1	1.06	1	1	1	1	1	1	1
Cd	5	1.5	1.4	1.51	1.72	1	1.06	1	1	1.75
Cr	100	70.27	161.9	5.5	16.6	10.6	8.03	5.65	10.31	9.32
Pb	15	24.03	16.5	20.4	13.1	5.88	13.9	8.7	12.5	15.9
Mn	1100	128.9	100	106.7	100	100	100	100	100	100
Hg	2	2	2.29	2	5.29	2	15	NA	11.8	9.75
Mo	120	11.07	237.4	10	10	10.4	10	10	10	10.62
Ni	100	65.94	75.56	50	64.88	50	69.52	50	53.05	57.94
Se	50	25	76.91	25	25	25	25	25	25	25
V	26	25	205.2	25.17	25	57.43	31.15	25	25	31.25
Zn	7300	714	390	633	1285	100	359	100	549	194

Table 4: Average Metal Leachate Concentrations (µg/Liter) (modified from [Morse 2003])

For example, because of the presence of phenols in foundry sand, there is some concern that precipitation percolating through stockpiles could mobilize leachable fractions, resulting in phenol discharges into surface or ground water supplies. Foundry sand sources and stockpiles must be monitored to assess the need to establish controls for potential phenol discharges [Johnson 1981, Ham 1989]. Table 5 presents the leachate results for Certified Reference Materials (CRMs) used in road construction.

Waste or Byproduct Material	Amendment Material	Organism Impact			Potential Toxicant	Conc. (mg/L)
		Raw Material Algal %EC50	Amended Material Algal %EC50	Amended Material *D. magna* %LC50		
Foundry Sand	AC	2	46	NTE	TOC	20
					Al	0.2
					Zn	0.03
Fly Ash	Aggregate	1.6	NTE	NTE	Al	0.24
					Zn	0.04
Crumb Rubber	AC	4	17	44	C_6H_4SCHN	0.45
					Al	1.5
					Hg	0.02

Table 5: 24-hr batch leaching results for Certified Reference Materials (CRMs) [Nelson 2003]

2) Recycling of Construction Aggregates

Besides the use of industrial byproducts, the demolition of pavements is also a source of materials to be reused in new pavements. Every year more than 200 million metric tons of recycled aggregates are generated in the U.S. [USGS 2000]. The recycling rate for asphalt pavements is approximately 85 percent [Wilburn 1998], but this varies from state to state in the U.S. Recycled aggregates are, however, increasingly being used to supplement natural aggregates in road construction in a variety of applications; 44 states allow their use in road base applications, 15 states for backfill, 8 states for Portland cement mix, and 7 states for top-course asphalt and other selected applications [Wilburn 1998]. However, more than 50% of all cement concrete waste and about 20% of all asphalt pavement debris still end up in landfills. An estimated 68% of recycled cement concrete debris is used as road base (Figure 2), with minor amounts used in asphalt concrete and as fill material. About 90% of recycled asphalt pavement is reused to make new asphalt pavements [Wilburn 1998].

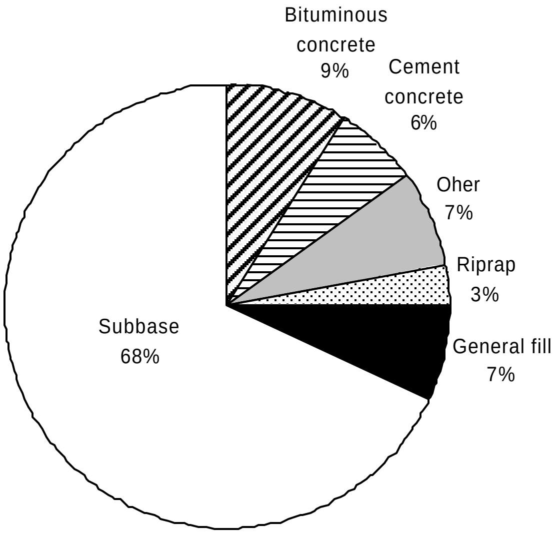


Figure 2: Final Use of Crushed Cement Concrete [Kelly 1998]

Figures 3 and 4 illustrate the flow of construction materials, looking at the difference between virgin aggregates and crushed concrete as aggregate. Because of the associated engineering properties, crushed cement concrete is usually used as a road base or subbase material.

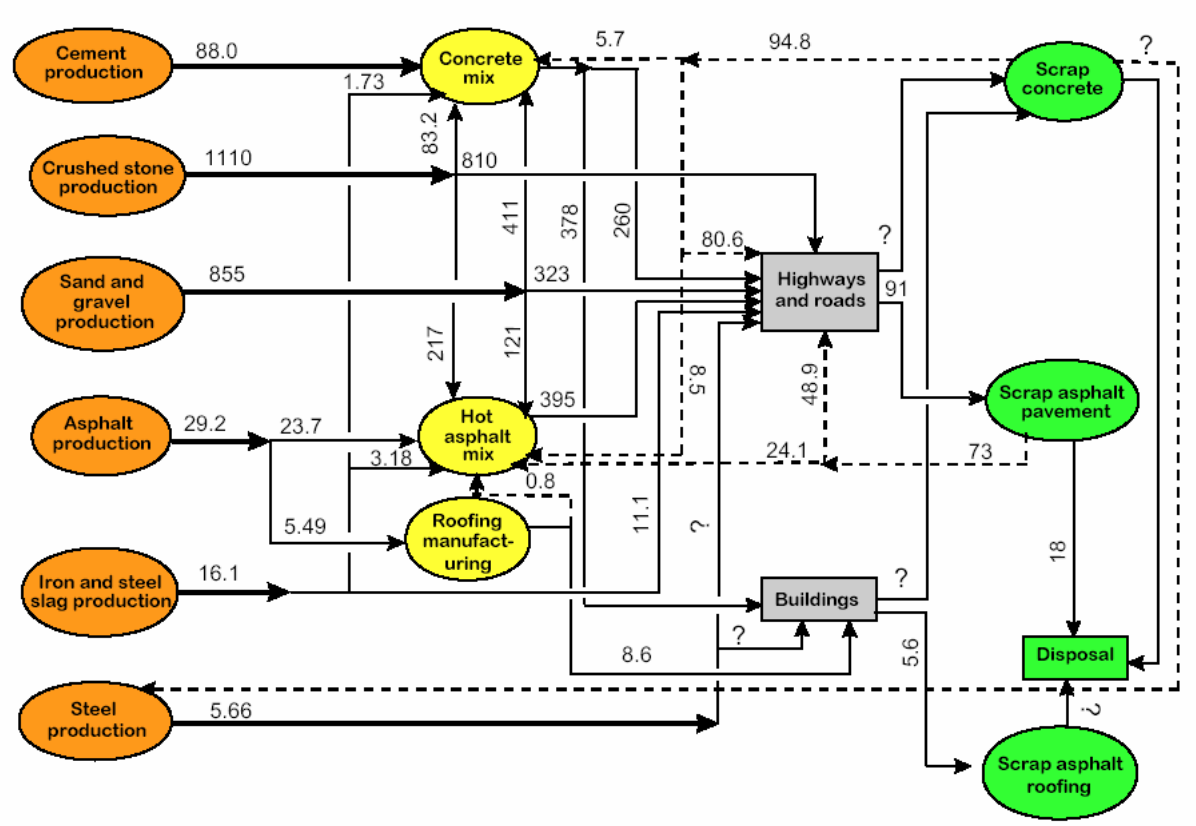


Figure 3: Flow of construction materials (construction aggregates vs. crushed concrete), 1996. Flows in million metric tons [Kelly 1998]

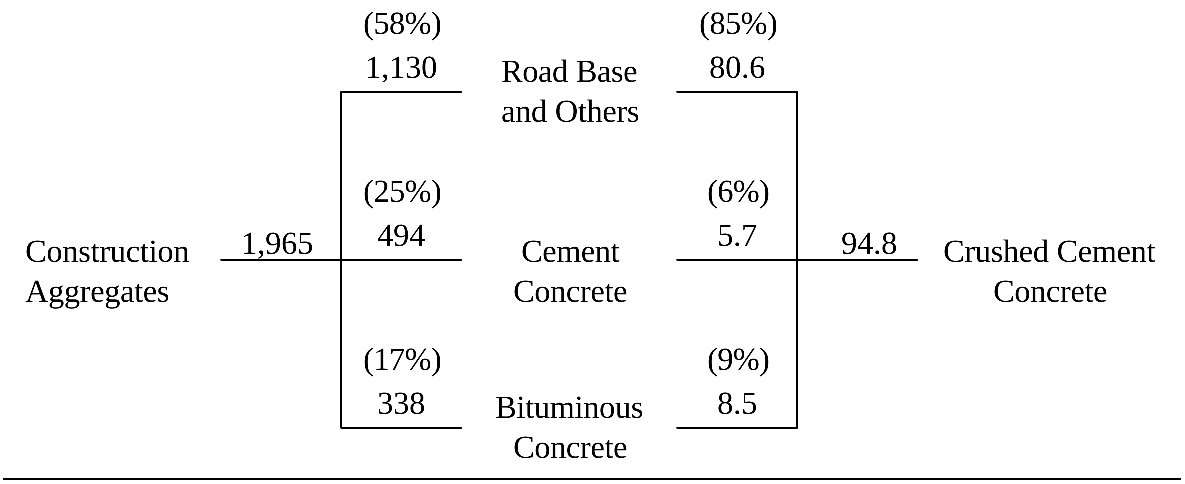


Figure 4: Flow into end uses (construction aggregates vs. crushed cement concrete). Flows in million metric tons. [Kelly 1998]

The annual amount of substitution of crushed cement concrete for construction aggregates is approximately 4.8%, according to the Portland Cement Association [Kelly 1998].

Approximately 100 million tons of crushed cement concrete substitute for construction aggregates, which are consumed at approximately 2 billion tons per year [USGS 200]. But the use of crushed cement concrete is rapidly increasing. More than half of the 81 companies contacted in a phone survey reported an increase in amount of recycled concrete from 1996 to 1997 [Kelly 1998]. Natural aggregate producers, who represent only part of crushed cement concrete producers, increased their production of recycled concrete by 37% between 1995 and 1996 [Kelly 1998, Bolen 1996]. Nationally, consumption of recycled aggregates from crushed concrete increased 170% between 1994 and 1996, but constituted less than 0.4 percent of total aggregates consumed in 1995 [Wilburn 1998].

In 1995, based on incomplete data, an estimated 45 million tons of recycled asphalt pavement (RAP) was produced in the U. S. [FHWA 1995]. In 1993, it was estimated that as much as 80 to 85 percent of RAP (approximately 36 million tons) is recycled for use in recycled hot mix asphalt, cold mixes, or as aggregate in granular or stabilized base materials [FHWA 1993]. Some of the RAP that is not recycled immediately is stockpiled and eventually reused.

Today, an estimated 100 million tons of old asphalt pavements are recovered annually. About 80 percent of the recovered material is currently recycled, and the remaining 20 percent are sent to landfills. Two-thirds of the recycled material is used as aggregates for road base. The remaining one-third of recycled material is reused as aggregates for new asphalt hot mixes [USGS 2000].

a) Economic Aspects

Financial considerations are a significant part of decisions to use RAP, in addition to environmental concerns. Florida DOT estimates $224 million in savings from the use of RAP since 1979 [Warren 1998], the equivalent of two thirds of their annual resurfacing budget. As of November 1998, Florida had 157 approved Superpave mix designs, and 117 of those designs, or 75 percent, included RAP. The amount of RAP ranges from 10 to 35% with an average of 20%. A Minnesota study estimated 18% savings if 40% RAP were used in HMA production [Olson 2003]. Other typical cost savings are shown for various government agencies, agencies and RAP percentages [Brown 1999] in Tables 6, 7 and 8.

Using RAP saves money for contractors and ultimately the state and local governments. In a 1998 Federal Highway Administration (FHWA) publication, “Pavement and Recycling Guidelines for State and Local Governments”, the authors estimated that the material costs for RAP are $8.20 per ton less than for virgin mix (this figure takes into account milling and transportation costs for RAP). On average, HMA producers can save about $1.50 per ton by including RAP as 20% of their asphalt mix [Jay 2000].

Published information from 1981 to 1991 suggests that, when all factors are considered, a savings up to 35% can be achieved when a 25 mm (1 in.) hot in-place recycled (HIPR) layer is compared with cold milling and placement of a new 25mm (1 in.) overlay (Button 1994). HIPR eliminates the costs associated with stockpiling, handling, and inventorying RAP. Since trucking of materials is may be reduced significantly if long haul distances of virgin aggregates could be eliminated, the costs of HIPR can be competitive. In many instances, additional cost savings can be realized because interruptions in traffic flow are less than with conventional rehabilitation techniques [Button 1994]. Typical average construction rates may range from 610 to 2,800 lane-miles (2000-9200 lane-ft) per day, depending on depth of scarification, pavement materials and temperature, recycling equipment, and traffic [Button 1994].

Agency	Average Savings, Percent
Florida	24-26
Georgia	4-8
New York	20
Wisconsin	10-13
FHWA	1-30
U.S. Corps of Engineers	16

Table 6: Agencies' Typical Cost Savings

Region	Average Savings, Percent
Northwest	24-26
Southwest	4-18
North Central	20
South Central	10-13

Table 7: Typical Cost Savings

Percent of RAP	Cost/ton	Savings $/ton	Savings %
0	11.9	-	-
20	10.26	1.64	14
30	9.44	2.46	21
40	8.62	3.28	28
50	7.8	4.1	34

Table 8: Material Cost Savings

In 1990, it was reported that the cost of heater-scarification to a depth of 25 mm (1in.) and incorporation of a recycling agent is approximately \$1.20/m^2 (\$1.00/yd^2) [Button 1994]. An additional 25mm (1in.) overlay costs approximately \$1.97/m^2 (\$1.65/yd^2). Therefore, to recycle and overlay a pavement in this manner using the two-pass method would cost approximately \$3.17/m^2 (\$2.93/yd^2). Cost savings up to 25% are reported over cold milling and overlaying using conventional procedures [Button 1994].

An HIPR roadtrain operating in Iowa eliminated the need for approximately 20 trucks and drivers and two loaders at the site of the road construction. This is beneficial for the environmental because it eliminates tailpipe emissions from construction equipment. The only trucks used were the ones that transported the recycled material from the end of the recycling line to the back where it was used immediately behind the vehicle to form the new replaced roadway. The productivity was 275 t/hr at a speed of 42 m/h. There were 3 diesel engines on the train (2 for the two crushers and one for everything else).

HIPR construction costs are generally lower than for conventional recycled hot mix because of lower transporting, processing, and stockpiling costs for the RAP. However, HIPR can only be used on roads without major structural deficiencies and projects that do not require significant changes to the mix [Button 1994].

International data about savings are also appearing in literature. Table 9 shows costs for in-plant hot-mix recycling of 1,000 kg of RAP in Belgium. Pavement material costs are reduced by approximately 26% if 40% RAP is used [De Bock 2003].

Compound	Part in the Composition of the Mixture (% m)	Unit Price (U.S. Dollars/ton)	HMA without Recycling	RHM with 40% Recycling
Stones	58	10	5.8	3.5
Sand	30	8	2.4	1.5
Filler	7	20	1.4	.84
Bitumen	5	100	5.0	3.0
RA	0-40%	5		2.0
Subtotal			**14.6**	**10.8**

Table 9: Calculation of the Cost Materials in a 1,000 kg batch of HMA [De Bock 2003]

Table 10 shows production costs other than those for materials.

Cost Element (U.S. dollars/ton HMA)	**Plant with no Recycling**	**Plant with Recycling**
investment in equipment + financing costs	1.48	2.04
maintenance of equipment	.45	0.78
quality control	.22	0.44
energy use	1.55	1.94
Subtotal	**3.80**	**5.20**

Table 10: Production Costs in Belgium [De Bock 2003]

The following assumptions were used for Table 10:

- "Asphalt mixing plant, with a yearly production of 200,000 ton hot mix, equipped for recycling with a parallel drum;

- “Recycling rate (mass RA on total mass HMA) of 40% for 100,000 ton/yr of binder/base courses, no recycling for wearing courses (also 100,000 ton/yr);
- “RA available on stock in plant, suitable for recycling, worth 5 USD/ton;
- “Investment cost for asphalt mixing plant: $3,700,000 (U.S. dollars)/yr versus $89,000 (U.S. dollars);
- “Higher energy demand for recycling: +15%; and
- “Extra costs for quality controls on RA and on recycled mixes (laboratory equipment + half-time personnel): +$22,000 (U.S. dollars)” [De Bock 2003].

Combining Tables 9 and 10 gives $18.40 per metric ton without recycling and $16.00 per metric ton if 40% RAP is used in Belgium [De Bock 2003].

b) Engineering Constraints

Limits have been established for the percentage of RAP in pavements. Most State Departments of Transportation (DOT) in the U.S. have technical specifications to accommodate the use of recycled asphalt pavement (RAP) in the construction of their roads. Table 11 shows a list of state DOTs and the maximum percentage of RAP allowed in the mixture.

State	Max. RAP% - Batch Plants			Max. RAP% - Drum Plants			Top Size for RAP
	Base	Binder	Surface	Base	Binder	Surface	
Alabama	40	40	15	50	50	15	2.0 in
Alaska	-	-	-	-	-	-	-
Arizona	30	30	30	30	30	30	1.5 in
Arkansas	70	70	70	70	70	70	3.0 in
California	50	50	50	50	50	50	2.0 in
Colorado	15	15	15	15	15	15	1.5 in
Connecticut	40	40	40	40	40	40	2.0 in
Delaware	35	35	25	50	50	30	2.0 in
Florida	60	50	None	60	50	None	Specs.
Georgia	25	25	25	40	40	40	2.0 in
Hawaii	30	None	None	40	None	None	1.5 in
Idaho	Open	Open	Open	Open	Open	Open	2.0 in
Illinois	50	25	15	50	25	15	Specs.
Indiana	50	50	20	50	50	20	2.0 in
Iowa	Open	Open	Open	Open	Open	Open	1.5 in
Kansas	50	50	50	50	50	50	2.0 in
Kentucky	30	30	30	30	30	30	Specs.
Louisiana	30	30	None	30	30	None	2.0 in
Maine	40	40	None	40	40	None	1.0 in
Maryland	Open	Open	Limit	Open	Open	Limit	Specs.
Massachusetts	20	20	10	40	40	10	0.8 in
Michigan	50	50	50	50	50	50	Specs.
Minnesota	59	50	30	50	50	30	3.0 in
Mississippi	30	30	15	30	30	15	2.0 in
Missouri	50	50	50	50	50	50	1.5 in

Montana	50	50	10	50	50	10	2.0 in
Nebraska	Not used	Not used	Not used	Open	Open	Open	2.0 in
Nevada	50	50	15	50	50	15	1.5 in
New Hampshire	35	35	15	50	50	15	Specs.
New Jersey	25	25	10	25	25	10	2.0 in
New Mexico							
New York							
North Carolina							
North Dakota							
Ohio							
Oklahoma	25	25	None	25	25	None	2.0 in
Oregon	30	20	20	30	20	20	1.0 in
Pennsylvania	Open	Open	Open	Open	Open	Open	2.0 in
Rhode Island	30	30	None	30	30	None	1.3 in
South Carolina	30	25	20	30	25	20	2.0 in
South Dakota	Not used	Not used	Not used	50	50	50	1.5 in
Tennessee	15	Open	None	Open	Open	None	Open
Texas	15	Open	Open	Open	Open	Open	2.0 in
Utah	Not used	Not used	Not used	25	25	25	2.0 in
Vermont	Specs.	Specs.	Specs.	Specs.	Specs.	Specs.	Specs. 2.0 in
Virginia	25	25	25	25	25	25	Open
Washington	Open	Open	Open	Open	Open	Open	Open
West Virginia	Open	Open	Open	Open	Open	Open	Open
Wisconsin	Open	35	20	Open	35	20	Open
Wyoming	50	50	50	50	50	50	2.0 in

Table 11: State DOT Specification Requirements for the Use of Reclaimed Asphalt Pavement (RAP) in Hot Mix Asphalt Paving Mixtures [Banasiak 1996]

c) Environmental Constraints

Environmental problems may yield an unfeasible recycling project. For example, the energy consumed to recycle materials from the demolition of a pavement may be higher than the energy consumed for the production, processing and transportation of virgin materials. Transport energy is fundamental to the environmental costs and benefits of recycling. A simple comparison between the processing and the transport energy for aggregates is shown in Figure 5.

Energy is only one of the possible environmental indicators, which is convenient because the production of energy is associated with various environmental impacts and the minimization of energy input in any activity always renders positive results. Other pollutants may also be considered (Table 12; all maintenance options include 25% of RAP).

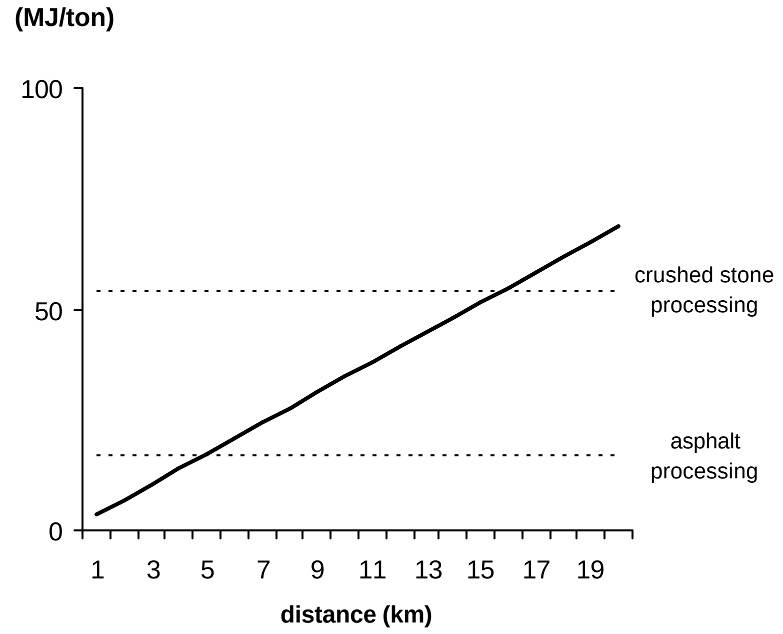


Figure 5: Processing Versus Transporting Energy for Asphalt Aggregates and Crushed Stone [Wilburn 1998]

	PARAMETERS					TOTAL EMISSIONS (g/m^2)				
Maintenance Options	Treated Depth (mm)	Overlay Depth (mm)	Emulsion Amount (%weight)	Life time (years)	Cost ($\$/m^2$)	CO_2	NO_x	SO_2	PM-10	TOC
CIR	101.6	50.8	1.50%	105	3.09	23,599	16	4	6	4
HIR-Surfacing	25.0			55		172	5	0.3	0.32	0.4
HIR Repaving	25	25		8	4.28	11,695	10.1	2	3.1	2.1
HIR-Remixing	40	19		8	3.58	8,964	7.9	1.6	2.4	1.6
HMA-Overlay		25		65		12,323	27.1	3.2	4.3	3.5

Table 12: Total Air Emissions Associated with Various Maintenance Options Using RAP

Sources of data: U.S.EPA/ AP-42-Compilation of Air Pollutant Emission Factors-Mobile Sources, Heavy-Duty Diesel Trucks, June 1995; U.S.EPA/ AP-42 Section 3.3 Gasoline and Diesel Industrial Engines-Emission Factor Documentation for, USEPA, October 1996; Forsberg, F., Lukanen, E., and Thomas, T. (2002) "Blue Earth County CSAH 20 – An Engineered Cold In-Place Recycling Project". 81st Annual Meeting of the Transportation Research Board. January 13-17, Washington, DC; Button, J.W., Estakhri, C.K., Little, D.N. (1995) "Performance and Cost of Selected Hot in Place Recycling Projects". Transportation Research Record. 1507 – Seal Coats and Asphalt Recycling.

However, most of the environmental and economic assessments of pavements lack a comprehensive view of the problem. That is, the analysis is based on a specific phase/material of the asphalt pavement, but does not cover the entire life cycle. The lack of a systemic assessment tool motivated the development of a tool to assess the life-cycle environmental and economic performance of pavements: the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE).

3) Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE)

PaLATE is a life-cycle analysis tool that draws on environmental and economic information to evaluate the use of different materials, including recycled materials, in the construction and maintenance of pavements. The tool calculates cumulative environmental effects such as energy consumption and air pollution releases over the period of analysis selected by the analyst, and the economic net present value and annualized cost of two concurrent options.

The computer-based decision-support tool integrates economic analysis and environmental assessment of pavements. On the economic side the tool calculates the net present value (NPV) of the pavement over its life-cycle and the annualized cost of the pavement. The tool allows for sensitivity analysis using different construction and maintenance schedules, and two different discount rates.

On the environmental side, PaLATE assesses emissions associated with materials production, construction, transportation, and maintenance of asphalt and portland cement concrete pavement, subbase, embankment and shoulder materials. It incorporates information about the use of both virgin and recycled materials (reclaimed asphalt and concrete, coal fly ash, coal bottom ash, blast furnace slag, glass, crumb rubber from tires).

PaLATE estimates energy consumption and emissions of CO_2, NO_x, PM_{10}, SO_2, CO, and informs average leachate releases for different construction materials. Environmental effects for initial construction, maintenance, and total are reported in bar graphs, and for each phase, effects from processes, materials transportation, and materials production are reported separately.

Description of PaLATE

The environmental and economic model of traditional and recycled materials for highway applications is implemented in an Excel tool named Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE). There is a website explaining the tool, its potentials, its structure, and its applications (www.ce.berkeley.edu/~horvath/palate.html).

The environmental and economic implications of pavement construction, maintenance, and materials recycling are subject to a set of complex interactions between various parameters. PaLATE is not a simple tool and some knowledge is required to carry out the analysis.

The incorporation of leachate information in the tool is based on averages for specific conditions and sites, and it is difficult to use such information in the model to predict leachate releases due to the use of construction materials. That is, leachate releases are also a function of water percolation in the pavement and drainage to a specific water body, which need to be locally assessed.

The tool is based on a life-cycle analysis (LCA) model and implemented in a computer-based spreadsheet that uses environmental and economic parameters to assist decision-makers in evaluating the use of recycled materials in highway construction applications and different maintenance options that rely on different percentages of recycled materials. PaLATE assesses the environmental and economic feasibility of pavement's recycling compared to the use of virgin materials.

Life-cycle costing (LCC) frameworks for pavements combine the cost of the infrastructure, its maintenance, and salvage value (agency costs) to the cost of traffic delays, damage to vehicles, accidents, etc. (user cost). PaLATE has a module that calculates the NPV of two pavement construction and maintenance alternatives and compares the effect of two discount rates. Because the periods selected by the analyst for the two possible options may differ, PaLATE also calculates the annualized cost for each of the alternatives.

The LCC framework integrated in PaLATE follows the recommendations of the Technical Bulletin of the Federal Highway Administration (Publication No. FHWA-SA-98-079), and PaLATE suggests values surveyed in the literature for several items in the cost module. Nevertheless, it encourages user inputs such as:

- Installed Asphalt Paving Cost
- Installed Concrete Paving Cost
- Installed Subbase & Embankment Construction Cost
- Hot in place recycling (HIPR) Cost
- Cold in place recycling (CIR) Cost
- Patching Cost
- Microsurfacing Cost
- Crack Sealing Cost
- Whitetopping Cost
- Rubblization Cost
- Full-depth Reclamation Cost

The incorporation of environmental costs is not yet considered in PaLATE but this feature could be added in the future. Currently, there are detailed traffic/technology driven models that calculate user emissions such as the MOBILE 6.2 model from EPA, and PaLATE fills an important niche of information that is the assessment of pollution arising from construction and maintenance of pavements. The economic evaluation of environmental impacts could lead to the inclusion of environmental effects in the cost module of PaLATE.

PaLATE suggests costs surveyed in the literature for various recycled materials and recycling activities; however, the user is encouraged to use her own cost estimations. The feasibility of recycling is strongly affected by material transportation costs and how such costs compare to the cost of new virgin material delivered to the construction site. When demolishing a pavement, both disposal cost of the material and its transportation cost should be considered. Palate suggests landfill tipping fees for all U.S. States to give an idea of the costs arising from the disposal of demolished material. The total disposal cost is compared to the cost of demolishing and transporting the material to a recycling facility where after some handling and processing the material is ready to substitute for virgin materials.

PaLATE uses a LCA framework to model the environmental effects of road construction and maintenance. The user defines the design of the pavement, which results in a given type and volume of construction materials, a given combination of construction activities, and a set of prescribed maintenance activities. The framework is implemented in an electronic spreadsheet, which handles data for the major phases of the pavement (Figure 6). Figure 6 implicitly represents the idea of perpetual pavements because there is no end-of-life for pavements. That is, the maintenance box may represent major reconstructions of a road's section that replaces the previous structure in that place. However, if part of the material is recycled and reused in the new structure, part may end up in a landfill. In summary, pavements may be perpetual but the materials used in their construction are not.

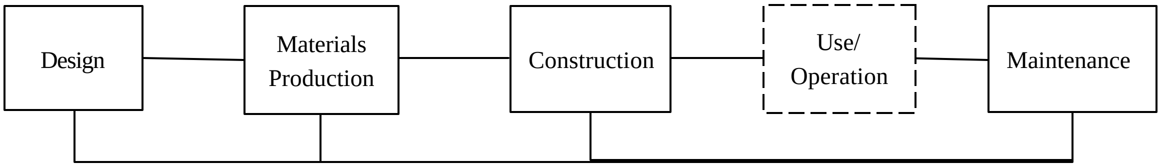
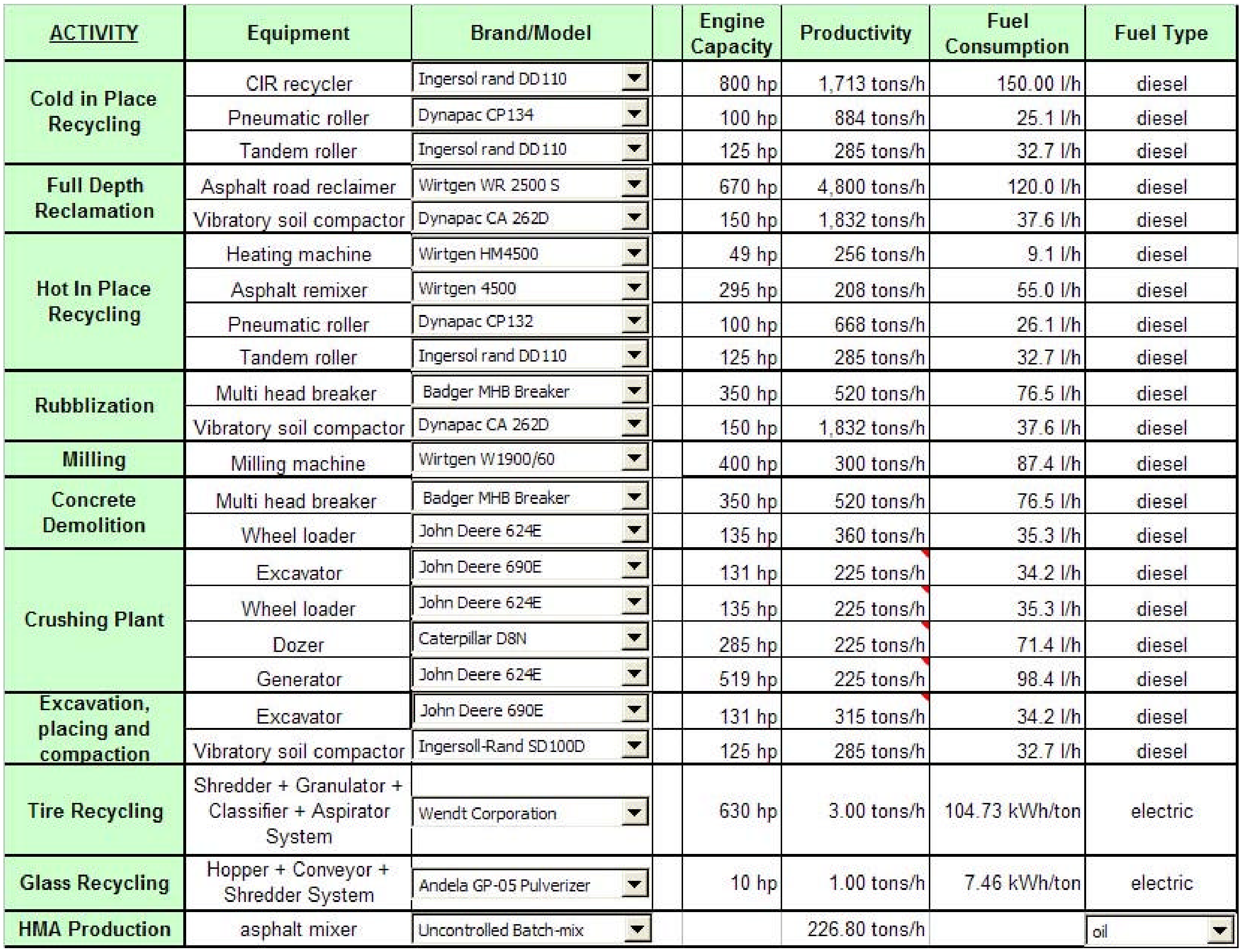


Figure 6: Life-cycle Phases of Pavements

The first module in the spreadsheet is the design module where the user defines the dimensions of each layer, the density of the construction materials, and the period of analysis. The period of analysis is used for discounting purposes as part of the economic assessment. The volume of the layers combined with the density of the materials calculates the mass of each material, which is used to determine the regime of operation of the construction equipment.

Environmental effects of using recycled materials depend on the characteristics of the equipment used to recover the materials, and the hauling of materials between processing facilities and the construction site. Energy use and air emissions are based on typical productivity, fuel consumption rate, and the engine size of the equipment used in each recycling activity. PaLATE allows for the selection of different equipment brand/models amongst the ones used in the various recycling activities (Figure 7). Besides the equipment used at the construction site, the tool includes choices for larger fixed equipment such as crushing and asphalt plants, and shredders. The analyst is encouraged to enter his own values and/or equipment type for a given task whenever the default values are not adequate.



ACTIVITY	Equipment	Brand/Model	Engine Capacity	Productivity	Fuel Consumption	Fuel Type
Cold in Place Recycling	CIR recycler	Ingersol rand DD110	800 hp	1,713 tons/h	150.00 l/h	diesel
	Pneumatic roller	Dynapac CP134	100 hp	884 tons/h	25.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Full Depth Reclamation	Asphalt road reclaimer	Wirtgen WR 2500 S	670 hp	4,800 tons/h	120.0 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Hot In Place Recycling	Heating machine	Wirtgen HM4500	49 hp	256 tons/h	9.1 l/h	diesel
	Asphalt remixer	Wirtgen 4500	295 hp	208 tons/h	55.0 l/h	diesel
	Pneumatic roller	Dynapac CP132	100 hp	668 tons/h	26.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Rubblization	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Milling	Milling machine	Wirtgen W1900/60	400 hp	300 tons/h	87.4 l/h	diesel
Concrete Demolition	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Wheel loader	John Deere 624E	135 hp	360 tons/h	35.3 l/h	diesel
Crushing Plant	Excavator	John Deere 690E	131 hp	225 tons/h	34.2 l/h	diesel
	Wheel loader	John Deere 624E	135 hp	225 tons/h	35.3 l/h	diesel
	Dozer	Caterpillar D8N	285 hp	225 tons/h	71.4 l/h	diesel
	Generator	John Deere 624E	519 hp	225 tons/h	98.4 l/h	diesel
Excavation, placing and compaction	Excavator	John Deere 690E	131 hp	315 tons/h	34.2 l/h	diesel
	Vibratory soil compactor	Ingersoll-Rand SD100D	125 hp	285 tons/h	32.7 l/h	diesel
Tire Recycling	Shredder + Granulator + Classifier + Aspirator System	Wendt Corporation	630 hp	3.00 tons/h	104.73 kWh/ton	electric
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer	10 hp	1.00 tons/h	7.46 kWh/ton	electric
HMA Production	asphalt mixer	Uncontrolled Batch-mix		226.80 tons/h		oil

Figure 7: Equipment details in PaLATE

Hauling distances are key factors for the environmental effects arising from the use of recycled materials. PaLATE requires the analyst to identify the transportation mode and the distances associated with every material, including recycled, used in the construction and maintenance activities. The selection of a given transportation mode combined with fuel efficiency and emission factors are used to calculate the environmental effects from transportation of recycled materials.

PaLATE reports environmental effects results disaggregated by initial construction and maintenance phases and by material production, transport, and processing. Figure 8 shows NO_x life-cycle emissions based on a case study.

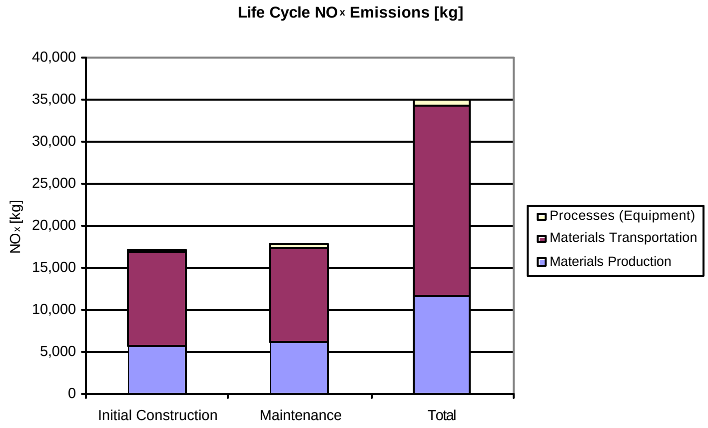


Figure 8: Life-cycle NO_x emissions

PaLATE, a computer-based decision-support tool that assesses environmental and economic effects of pavements and roads has been created. The tool takes user input for the design, initial construction, maintenance, equipment use, and costs for a roadway, and provides outputs for the life-cycle environmental effects and costs. Environmental effects investigated include:

- Energy consumption
- CO_2 emissions
- NO_x emissions
- PM_{10} emissions
- SO_2 emissions
- CO emissions
- Water consumption
- Mercury
- Lead
- Leachate information

Pavement designers, transportation agency decision-makers, civil engineers, and researchers are the intended users of this tool. Users should have a working knowledge of pavements and a desire to learn more about the environmental and economic implications of their decisions.

PaLATE users may enter data about an existing, proposed, or hypothetical roadway to determine the environmental and economic effects of their decisions. Some example questions that the user may keep in mind when working with PaLATE are:

- For a particular roadway, which material is better for the environment: concrete or asphalt?
- Will changing the recycled material content in a particular pavement affect the environmental results?

- Does sending demolished portions of a road to a processing plant or to a landfill makes more environmental and economic sense?
- Which maintenance option(s) will minimize environmental and economic effects? For example, should full depth reclamation be performed instead of more frequent, smaller maintenance procedures?
- Will changing the type and/or capacity of equipment used on-site reduce emissions?
- How much of a difference do materials transportation distance and mode make for my case study? For example, should I use materials from a local source to reduce emissions? Is it better to transport via rail or truck?

The tool takes the user through a series of input worksheets to gather data about:

- the general design of the roadway
- initial construction materials as well as material transportation distances and modes
- maintenance materials as well as material transportation distances and modes
- on-site construction equipment (e.g., asphalt paver) and off-site processing equipment (e.g., rock crusher)
- life-cycle economic costs

Case Study

A case study is used to demonstrate the potential of PaLATE. In this study a 3 layer road is considered (Table 13). Table 14 shows the materials, densities and volumes used in the case study.

Results from PaLATE show (Figure 9) that materials production and transportation are responsible for the majority of the energy consumption.

Layer Specifications				
Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	24	1	3	1,173
Wearing Course 2	25	1	7	2,852
Wearing Course 3				0
Subbase 1	28	1	24	10,951
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			**34**	14,976

Table 13: Characteristics of Layers and Material Volumes for Roadbase in PaLATE

Layer	Material	Density (tons/yd^3)	Volume (yd^3)
Wearing Course 1	Virgin Aggregate	1.25	1,123
	Bitumen	0.84	50
Wearing Course 2	Virgin Aggregate	1.25	1,200
	Bitumen	0.84	152
	RAP transportation	1.85	1,200
	RCM transportation	1.88	0
	Coal Fly Ash	2.2	50
	Coal Bottom Ash	2	0
	Blast Furnace Slag	1	0
	Recycled Tires/ Crumb Rubber	1.92	150
	Glass Cullet	1.93	100
	RAP from site to landfill	1.85	100
Subbase 1	RAP to recycling plant	1.85	3,000
	RAP from recycling plant to site	1.85	3,000
	RCM to recycling plant	1.88	2,451
	RCM from recycling plant to site	1.88	2,451
	Gravel	1.35	4,000
	Sand	1.25	1,500
	Total: Subbase 1 materials to site	**1.68**	**10,951**
	RAP from site to landfill	1.85	300
	RCM from site to landfill	1.88	245

Table 14: Materials and Volumes Used in Case Study

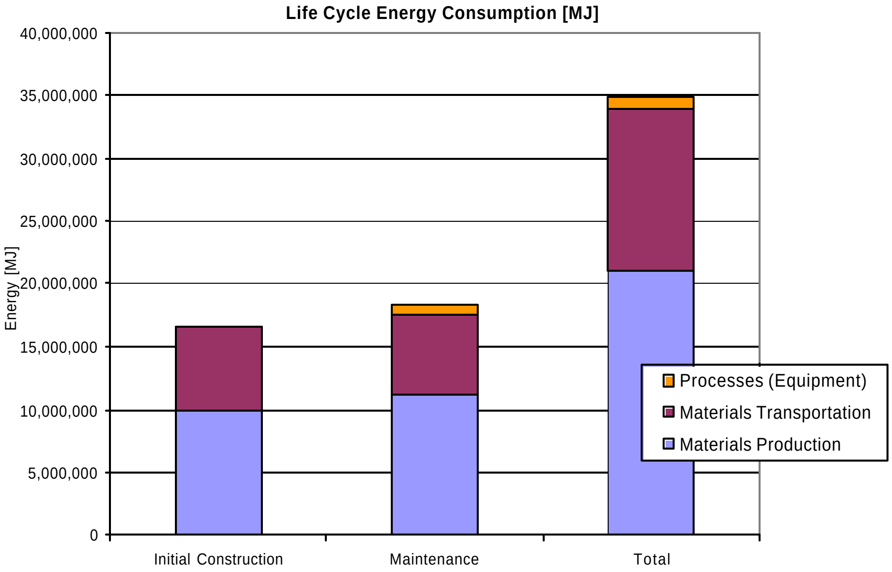


Figure 9. Life-cycle energy consumption for a case study.

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Appendix 1: Number of Municipal Solid Waste Landfills by State, Average Tipping Fee, and Remaining Capacity in 2000 [Goldstein 2001]

State	*Number*	*Average Tip Fee ($/ton)*	*Remaining Capacity (years)*
Alabama	29	$30.00	10
Alaska	275		0-100
Arizona	49	$26.11	
Arkansas	23		30
California	175	$35.14	18
Colorado	70	$11.00	
Connecticut	2		3
Delaware	3	$58.50	30
District of Columbia	0		
Florida	61	$42.85	
Georgia	69	$29.18	23.5
Hawaii	9	$50.00	15
Idaho	29		
Illinois	52	$30.68	15
Indiana	36	$29.92	13.5
Iowa	61	$33.00	60
Kansas	51		20+
Kentucky	26	$27.24	15.2
Louisiana	23	$22.85	
Maine	8	$65.00	15
Maryland	23	$49.00	>10
Massachusetts	21	$67.00	<2
Michigan	54		15
Minnesota	22	$40.00	7
Mississippi	20	$25.00	20
Missouri	25	$29.53	9
Montana			
Nebraska	23	$25.00	
Nevada	24	$18.00	>50
New Hampshire	15	$66.00	8
New Jersey	12	$55.00	12
New Mexico	44	$32.00	20
New York	27		7
North Carolina	42	$31.00	
North Dakota	14	$25.00	20
Ohio	44	$29.00	22
Oklahoma	40	$20.00	20
Oregon	29	$25.00	40
Pennsylvania	49		12
Rhode Island	4	$40.00	10
South Carolina	19		>13
South Dakota	15	$31.00	25-30
Tennessee	48	$28.76	
Texas	227	$25.46	32
Utah	37		100
Vermont	5	$75.00	6.3
Virginia	67		20
Washington	21	$49.79	51
West Virginia	18	$42.37	30
Wisconsin	44	$38.00	5
Wyoming	58		
Total	**2,142**		

Appendix 2: Fly Ash Properties [MOEE 1993]

***Compressive Strength*:** The strength development in flowable fill mixtures is directly related to cement content and water content, particularly when Class F fly ash is used. Most high fly ash content mixes only require from 3 to 5 percent Portland cement by dry weight of fly ash to develop 28-day compressive strengths (517 to 1034 kPa - 75 to 150 lb/in^2). For low fly ash content mixes, Class C fly ash contributes to the strength development and can also be a complete replacement for Portland cement. As the water content is increased to produce a more flowable mix, compressive strength development will probably be somewhat lowered.

***Flowability*:** Flowability or fluidity is a measure of how well a mixture will flow when being placed. The higher the water content is, the more flowable the mix is. Flowability can be measured using a standard concrete slump cone, a flow cone, or a modified flow test using an open ended 75 mm (3 in) diameter by 150 mm (6 in) high cylinder. Flowability ranges associated with the standard concrete slump cone (ASTM C143) generally vary from 150 mm (6 in) to 200 mm (8 in). Admixtures (such as water reducing agents) are not normally used in flowable fill.

For high fly ash content flowable fill mixes, the slump ranges can be expected to be at least 25 to 50 mm (1 to 2 in) higher than low fly ash content mixes at comparable moisture contents.

The flow cone test (ASTM C939) is a standard procedure for determining the flow rate of grout. A desirable rate of flow for most applications of flowable fill is a time of 30 to 45 seconds through a standard flow cone. The modified flow test involves filling a 75 mm (3 in) diameter by a 150 mm (6 in) cylinder mold with flowable fill, emptying the contents of the cylinder on a flat surface, and measuring the diameter of the spilled flowable fill. This test is best suited to mixtures that contain primarily fine aggregates (low fly ash content mixtures). For good flowability, the diameter of the spread material should be at least 200 mm (8 in).

***Stability*:** For low fly ash content flowable fill materials, triaxial strength tests have indicated friction angles of 20° for mixes containing fine sand and up to 30° for mixes containing concrete sand. Cohesion measured from triaxial testing has been found to vary with the compressive strength. Mixes with a 344 kPa (50 lb/in^2) compressive strength have exhibited 120 kPa (2,500 lb/ft^2) cohesion, while mixes with a 690 kPa (100 lb/in^2) compressive strength have exhibited 200 kPa (4,200 lb/ft^2) cohesion.

***Bearing Capacity*:** The allowable bearing capacity of hardened flowable fill has been shown to vary directly with compressive strength and friction angle. For example, the allowable bearing capacity for flowable fill with compressive strength of 690 kPa (100 lb/in^2) may range from 78 metric tons/m^2 (8 tons/ft^2) at a 20° friction angle to 156 metric tons/m^2 (16 tons/ft^2) at a 30° friction angle. This is approximately two to four times the bearing strength of most well- compacted granular soil fill materials.

California Bearing Ratio (CBR) is also a measure of the in-place bearing strength of a subgrade material compared with that of standard crushed stone. Previous testing has exhibited CBR values ranging from 40 to 90 percent. CBR testing of typical 690 kPa (100 lb/in^2) flowable fill resulted in a CBR value of 50 within 24 hours of placement. As the compressive strength of the flowable fill material increases, the CBR value can be expected to increase.

***Modulus of Subgrade Reaction*:** The modulus of subgrade reaction (k), used for the design of rigid pavement systems, is usually in the range of 8.2 to 49.2 N/cm^3 (50 to 300 lb/in^3) for most soils and 82 N/cm^2 (500 lb/in^3) for a good granular subbase material. The k value for flowable fill is usually 820 N/cm^2 (5,000 lb/in^3) or higher, meaning it is superior to any earthen backfill it would replace.

***Time of Set*:** For most flowable fill mixes, especially those with high fly ash content, an increase in the cement content or a decrease in the water content, or both, should result in a reduction in hardening time. Typical high fly ash content flowable fill mixes (containing 5 percent cement) harden sufficiently to support the weight of an average person in about 3 to 4 hours, depending on the temperature and humidity. Within 24 hours, construction equipment can operate on the surface without apparent damage. Some low fly ash content flowable fill mixes, especially those containing self-cementing fly ashes, have hardened sufficiently to allow street patching within 1 to 2 hours following placement.

***Bleeding and Shrinkage*:** High fly ash content flowable fill mixes with relatively high water contents tend to release some bleed water prior to initial set. Evaporation of the bleed water often results in a shrinkage of approximately one percent (1/8 in per ft) of flowable fill depth. The shrinkage may occur laterally as well as vertically. No additional shrinkage or long-term settlement of flowable fill occurs once the material has reached an initial set. Low fly ash content mixes, because of their high fine aggregate content and ability to more readily drain water through the flowable fill, tend to exhibit less bleeding or shrinkage than high fly ash content mixes.

***Density*:** High fly ash content flowable fill mixes are usually lighter than compacted natural soils. Typical wet density values may range from 1460 to 1945 kg/m^3 (90 to 120 lb/ft^3), with the material being heaviest when first placed. Low fly ash content flowable fill mixes may have wet density values ranging from 1785 to 2190 kg/m^3 (110 to 135 lb/ft^3).

***Permeability*:** Permeability values for high fly ash content flowable fill mixtures have been found to decrease with increasing cement content and are generally in the range of 10^{-6} to 10^{-7} cm/sec. Although few data are available regarding the permeability of low fly ash content flowable fill mixtures, the permeability of such mixtures is greater than that of high fly ash content mixtures, apparently in the 10^{-4} to 10^{-6} cm/sec range.