ENGINEERING ECONOMY AND ENERGY CONSIDERATIONS

ENERGY REQUIREMENTS ASSOCIATED WITH PAVEMENT CONSTRUCTION, REHABILITATION AND MAINTENANCE

RESEARCH REPORT 214-19

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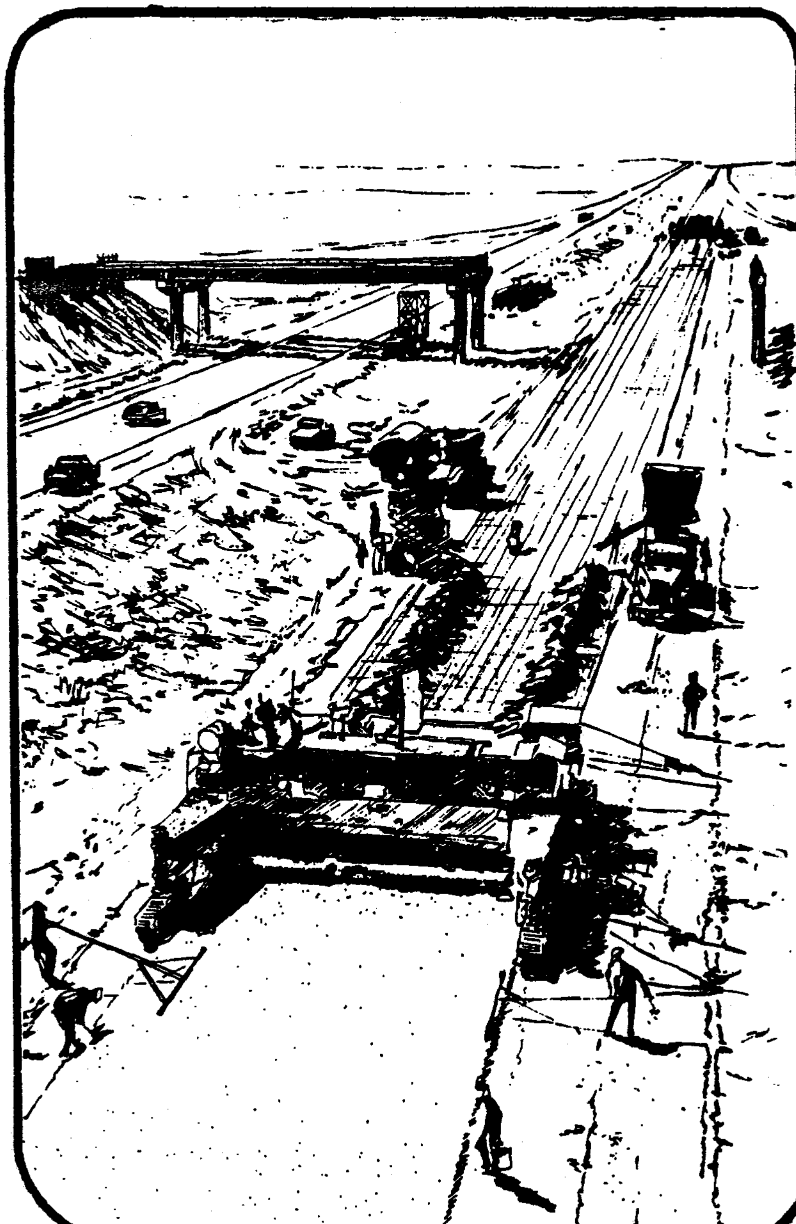

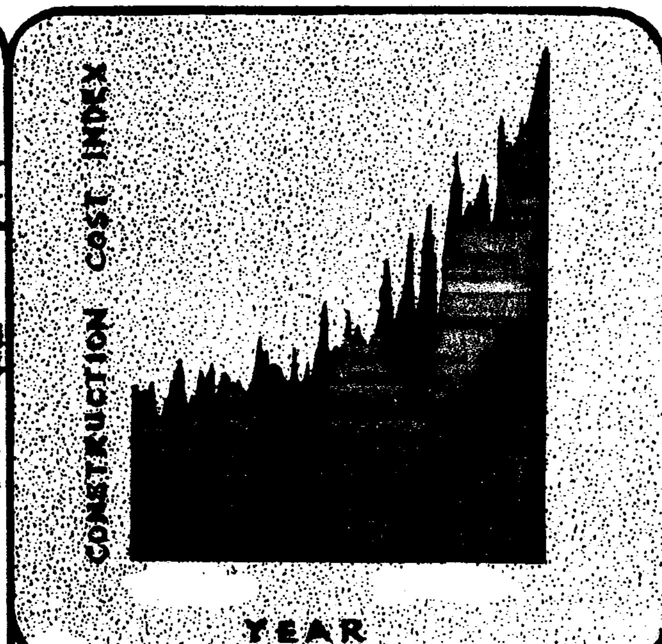

COOPERATIVE RESEARCH PROJECT 2-9-74-214

"ENGINEERING, ECONOMY AND ENERGY CONSIDERATIONS IN DESIGN, CONSTRUCTION AND MATERIALS"

TEXAS STATE DEPARTMENT OF HIGHWAYS AND PUBLIC TRANSPORTATION

AND

TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY

ENERGY REQUIREMENTS ASSOCIATED WITH PAVEMENT CONSTRUCTION, REHABILITATION AND MAINTENANCE

by

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INTRODUCTION

Transportation of goods and services required 25 percent of the total 90 quadrillion (10^{15}) Btu (95,000 quadrillion J) consumed in the United States in 1977. This amount increases to 42 percent if the total amount of energy required for 1) the production of raw materials used in transportation vehicles, 2) manufacture of transportation vehicles and 3) the production of materials for construction, rehabilitation and maintenance of transportation facilities is considered.

Estimates of the energy consumed for highway construction are of the order of 1.7 percent of the total annual U. S. energy demand while maintenance and rehabilitation operations are estimated to require an additional 1.5 to 2.0 percent (14). Information included below indicates that a reasonable energy estimate for routine pavement maintenance operations on our country's 3,800,000 mile highway system is 0.1 percent. Even with this relatively small percent of total energy consumption associated with highway construction and maintenance, it is none-the-less important that the engineer optimize these operations based on energy requirements just as he presently optimizes his operations based on cost.

Information included below defines energy requirements for operations associated with pavement construction, rehabilitation and maintenance. These energy requirements are intended to be representative only. If energy requirements for these operations are available from the agencies' historical records, they should be substituted appropriately.

The preferred approach for calculation of the energy requirements is to use a step-by-step procedure for each phase of the construction, rehabilitation, or maintenance operation utilizing the energy data summarized below. Since this is a time consuming process, summary data is also presented for several operations. These data can be utilized for a number of purposes as outlined below:

1. Define energy requirements of selected maintenance and rehabilitation operations,
2. Identify energy intensive maintenance operations,
3. Identify energy efficient operations,
4. Assess the impact of fuel allocation programs,
5. Define energy associated with maintenance equipment operation,
6. Evaluate energy demand of new construction, rehabilitation, and maintenance operations,
7. Identify where fuel savings can be obtained from an operational standpoint and
8. Determine total and/or equal annual energy requirements for various pavement and/or rehabilitation strategies for a 20 to 30 year period and thus allow the engineer to select the most viable alternative based on both cost and energy.

ENERGY EQUIVALENTS

A wide variety of equipment and processes are utilized to produce, transport, and place materials associated with highway construction, rehabilitation and maintenance activities. Typical equivalencies for a wide variety of fuels associated with these operations are shown in Table 1. It should be noted that as the density of the petroleum product increases, the energy value increases. Asphalt cement, which has a relatively high density has a large energy equivalent. It should be noted that asphalt has not been considered as a fuel source but rather as a construction material in this report. Thus, if asphalt cement, cutback asphalt, or emulsified asphalt are materials utilized as a part of the maintenance or rehabilitation activity, their energy equivalencies as a fuel are not considered (2). The potential is there, however.

To aid the reader in conversion from one energy unit to another energy unit, the following is offered:

1 kWh	= 3412 Btu
1 hp-hr	= 2547 Btu
1 hp	= 0.7457 kW
1 kWh	= 1.341 hp
1 Btu	= 1055 J
1 J	= 0.000948 Btu

A British thermal unit (Btu) is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit when water is at or near 39.2°F (4°C). A Joule is a unit of work and energy in the SI System. 4.186 Joules are required to raise 1 gram of water 1°C.

EQUIPMENT

Energy requirements for various types of vehicles and equipment associated with construction, rehabilitation and maintenance are shown in Tables 2 and 3. Table 2 gives energy requirements for automobiles and trucks while Table 3 includes various maintenance equipment. Appropriate references are included. Truck energy requirements are based on a loaded truck one way with an empty return trip. Thus the total round-trip mileage should be multiplied by the values in the table to get the energy required for hauling.

PRODUCTION AND MANUFACTURE

Energy requirements for the manufacture of binders used in pavement construction, rehabilitation and maintenance operations are shown in Table 4. The values shown represent average values. Btu requirements for the various grades of emulsified asphalt are shown in Table 5. The values shown in this table do not include the energy associated with the possible addition of solvent. Where applicable, 1350 Btu should be added for each percent of added solvents. Solvents are often used with medium setting emulsions (7).

Table 6 shows the Btu requirements for the production of all grades of cutback asphalts. Depending on the type and grade, approximately 20 to 50 percent petroleum distillate is used in combination with an asphalt cement. Data presented in Table 6 considers the distillate as an energy source and thus the Btu value of the appropriate distillate has been included in the production energies given (7).

Btu requirements for producing reinforcing steel bars for use in concrete construction are shown in Table 7. Data presented in this table are based on 24,000,000 Btu per ton (7).

Energy associated with operations involving the production of aggregates, asphalt concrete and portland cement concrete are shown in Tables 8, 9 and 10. Some of the data contained in Table 9 has been recently revised by The Asphalt Institute. Data are shown in Table 11 for both batch and dryer-drum mixing plants. In some cases different values have been reported by various agencies. These differing values are given in the tables.

CONSTRUCTION OPERATIONS

Energy consumption for materials utilized in pavements (in-place) are given in Table 12. Materials included in the table are asphalt concrete, portland cement concrete, slurry seal, chip seal, fog seal, crushed stone base, and emulsified asphalt base. The energy consumed included the energy associated with manufacturing, mixing, hauling, placing and compacting. Haul distances for these calculations are of the order of 10 to 30 miles. Requirements for miscellaneous construction operations are shown in Table 13.

Energy requirements for individual asphalt distribution operations are shown in Table 14 for spraying asphalt cement, cutback asphalt and emulsified asphalt (7). The differences in energy requirements are due to the spraying temperature requirements for the various asphalts.

MAINTENANCE AND REHABILITATION OPERATIONS

Energy requirements associated with the performance of routine maintenance and rehabilitation activities are shown in Table 15. The specific activities for which energy data have been calculated are:

1. Fog Seal - Partial Width
2. Fog Seal - Full Width
3. Chip Seal - Partial Width
4. Chip Seal - Full Width
5. Surface Patch - Hand Method
6. Surface Patch - Machine Method
7. Digout and Repair - Hand Method
8. Digout and Repair - Machine Method
9. Crack Pouring
10. Slurry Seal
11. Asphalt Concrete Overlay

Energy required for material manufacture, material transportation, mixture production, mixture transportation, mixture placement and compaction is included in the data in previous tables. Assumptions as to the percent of the pavement area treated with the particular maintenance activity and the thickness or quantity of material applied are identical to those used for estimating rehabilitation and maintenace costs (15). These data were developed based primarily on information obtained from the states of Arizona, Nevada and North Dakota.

RECYCLING OPERATIONS

Energy requirements associated with the performance of recycling operations are shown in Table 16. These data are based on information obtained from equipment manufacturers and contractors.

LIFE CYCLE ENERGY

Due to the high cost of energy and a possible restricted future supply of energy, the engineer must now evaluate energy on a life cycle basis and an initial basis for various pavement rehabilitation and maintenance strategies. The data to be used in these calculations is available in this report. A method for calculating life cycle energies is described below.

EXAMPLE PROBLEM

An interstate highway pavement located in West Texas is in need of rehabilitation. The existing pavement has 8 inches of flexible base course and 4 inches of asphalt concrete. Ten rehabilitation alternatives are presently under consideration. These alternatives are briefly defined in Table 17. The rehabilitation and maintenance schedule for the various alternatives as identified by cost are shown in Table 18. Example calculations associated with energy requirements for Plans 1 and 7 are shown in Table 19. Data contained in this report were used as a basis for the calculations. Routine maintenance anticipated for the various alternatives is crack pouring. For convenience, a blank calculation form has been included as Table 20.

The energy consumption associated with each alternative on both a 20-year life cycle and first rehabilitation activity basis are shown in Table 21.

The energy consumption associated with a non-asphalt or non-bituminous alternative has been calculated as 1,144,000 Btu per square yard over a 20-year life. This is approximately 7 times more energy-intensive than the asphalt rehabilitation approaches. It should be noted that the energy data shown in Table 21 does not include the fuel value of asphalt. If data were presented which contained this intrinsic energy value, the energy consumptions of asphalt versus non-asphalt rehabilitated and maintained pavements would be approximately equal.

CONCLUSIONS AND RECOMMENDATIONS

1. Energy requirements have been presented for a wide range of construction, rehabilitation and maintenance operations. In addition, energy requirements for material production and various operations have been summarized.

2. These data will allow the engineer to calculate life cycle energy requirements for various rehabilitation strategies. Energy data can be compared with life cycle cost information and used for selection of the most appropriate rehabilitation strategy.

3. Data presented can be utilized by the engineer to identify these operations which are energy intensive. Efforts to conserve energy should concentrate on those operations first.

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Table 1. Fuel Equivalents.

Fuel	Energy Equivalent
Gasoline	125,000 Btu/Gal (1)
Kerosene	135,000 Btu/Gal (1)
Fuel Oil, No. 1 (API 42)	135,000 Btu/Gal (1)
Fuel Oil, No. 2 (API 35) (Diesel)	139,000 Btu/Gal (1)
Fuel Oil, No. 3 (API 28)	143,000 Btu/Gal (1)
Fuel Oil, No. 4 (API 20)	148,500 Btu/Gal (1)
Fuel Oil, No. 5 (API 14)	152,000 Btu/Gal (1)
Fuel Oil, No. 6 (API 10) (Bunker C)	154,500 Btu/Gal (1)
Natural Gas	1,000 Btu/Ft (1)
Propane Gas	91,000 Btu/Gal (1)
Butane Gas	100,000 Btu/Gal (1)
Asphalt Cement	158,000 Btu/Gal (2,3) 19,045 Btu/lb
Coal	11,670 Btu/Lb (4)
Petroleum Coke	14,470 Btu/Lb (4)
Lignite	6,000 to 9000 Btu/Lb

Metric Conversion:

1 Btu/Gal = 278.7 J/l

1 Btu/Ft^3 = 37.26 J/l

1 Btu/Lb = 2324 J/kg

Table 2. Energy Requirements for Automobile and Truck Operation.

Type of Vehicle	Energy Requirements Btu/Mi	Btu/Hr	Btu/Ton Mi	Ref.
Automobile	7,230			5
Stationwagon	7,760			5
Pickup	11,400			5
Maintenance Trucks--Diesel	26,700	97,300		5
Maintenance Trucks--Gasoline	26,600	100,000		5
Maintenance Trucks--1 Ton	15,600			5
Maintenance Truck--2 Axle	27,500			5
Distributor Truck--Gasoline	31,300			5
Truck Tractor--Diesel	30,400			5
Truck--2 Axle, 6 Tire, Gasoline			11,000	1
Truck--3 Axle, Gasoline			4,270	1
Truck--3 Axle, Diesel			3,800	1
Truck--3 Axle, (combination) Gasoline			7,440	1
Truck--3 Axle, (combination) Diesel			5,840	1
Truck--4 Axle, (combination) Gasoline			5,040	1
Truck--4 Axle, (combination) Diesel			3,270	1
Truck--5 Axle, (combination) Gasoline			2,900	1
Truck--5 Axle, (combination) Diesel			1,960	1

Metric Conversion:

1 Btu/Mi = 656.1 J/km

1 Btu/Hr = 1055 J/hr

1 Btu/Ton mi = 0.723 J/kg km

Table 3. Energy Requirements for Miscellaneous Maintenance and Rehabilitation Equipment.

Type of Vehicles	Energy Requirement		Ref.
	Btu/Mi	Btu/Hr	
Front End Loader--2 cu yd, Diesel		6,950	5
Front End Loader--1.5 cu yd, Gasoline		5,000	5
Loader for Aggregates		875,000	1
Front End Loader, Diesel		222,000	1
Motor Grader--23,000 lb., Diesel		6,950	5
Grader, Diesel		375,000	5
Rollers		625,000	1
Roller		111,000	5
Striping Machine, Self Contained		125,000	5
Hand Striping Machine		62,500	5
Mower, Roadside		125,000	5
Mower, Landscape		46,800	5
Tractor, Farm Type		375,000	5
Spreader, Self Propelled		338,000	5
Broom, Mechanical		125,000	5
Dozer, Track Type		417,000	5
Crushing/Screening Plant		695,000	5
Asphalt Paver		626,000	1

Metric Conversion:

1 Btu/Mi = 656.1 J/km

1 Btu/Hr = 1055 J/hr

Table 4. Energy Associated with Manufacturing.

Item	Energy Requirements			Ref.
	Btu/Gal	Btu/Lb	Btu/Ton	
Asphalt Cement	2,500	300	600,000	1
Emulsified Asphalt	2,000	240	480,000*	1
Cutback Asphalt	2,500	300	600,000**	1
Portland Cement		3,150	6,300,000***	6
Steel, for tiebars, re-bars		10,500 12,000	21,000,000 24,000,000	1 7
Lime		3,000 3,750	6,000,000 7,500,000	1 7
Polyhydrate		1,500	3,000,000	

*For equal quantities of binder this is equivalent to 740,000 Btu/Ton. Assumes 65 percent residual asphalt.

**For equal quantities of binder this is equivalent to 750,000 Btu/Ton. Assumes 80 percent residual asphalt.

***Other values for Portland Cement reported in the literature are 7,500,000 (1,3) and 7,110,000 (7) Btu/Ton.

Metric Conversion:

1 Btu/Gal = 278.7 J/l

1 Btu/Lb = 2324 J/kg

1 Btu/Ton = 1.164 J/kg

Table 5. Btu Required to Produce One Gallon Emulsified Asphalt*.

Anionic		Cationic	
RS-1	2565	CRS-1	2640
RS-2	2685	CRS-2	2715
MS-1	2565	-	-
MS-2	2715	CMS-2	2715
MS-2h	2715	CMS-2h	2715
SS-1	2595	CSS-1	2595
SS-1h	2595	CSS-1h	2595

*These values do not include the energy associated with the possible addition of solvent. Where applicable, 1350 Btu should be added for each percent of added solvent.

After Reference 7.

Table 6. Btu Required to Produce One Gallon Cutback Asphalt.

Grade	Type			Gal/Ton
	RC	MC	SC	
-30	-	70,000	-	256
-70	58,800	63,200	72,000	253
-250	46,200	47,000	58,100	249
-800	33,800	36,200	44,200	245
-3000	27,500	29,500	30,300	241

After Reference 7.

Table 7. Btu Required to Produce Reinforcing Bars.

Bar Designation Number	Nominal Diameter, In.	Unit Weight, Lb per Ft	Btu/Ft
2	0.250	0.167	2.004
3	0.375	0.376	4.512
4	0.500	0.668	8.016
5	0.625	1.043	12.516
6	0.750	1.502	18.024
7	0.875	2.044	24.528
8	1.000	2.670	32.040

After Reference 7.

Table 8. Energy Associated with Aggregate Production.

Product	Operation	Energy Requirement			Ref.
		Btu/Lb	Btu/Ton	Btu/Yd^{3*}	
	Drilling and shooting	6	12,000	21,000	1
	Crushing	25.5	51,000	89,500	1
Crushed Stone	Handling (cranes and and bulldozers)	3.5	7,000	12,300	1
	Total	35	70,000	123,000	1
	Total	26 18 28	52,000 36,000 56,000	91,300 63,200 98,300	8 7 7
	Crushing	17.5	35,000	61,400	1
Crushed Gravel	Handling (cranes and bulldozers)	2.5	5,000	8,780	1
	Total	20	40,000	70,000	1
Natural or Uncrushed Aggregate	Total	7.5	15,000	26,300	1

*130 Lbs/Ft^3 assumed unit weight (2100 km/m^3).

Metric Conversion:

1 Btu/lb = 2324 J/kg

1 Btu/Ton = 1.164 J/kg

1 Btu/Yd^3 = 1381 J/m^3

Table 9. Energy Associated with Asphalt Concrete Production*.

Operation	Energy Requirements			
	Btu/Ton of Mix	Operation**	Equiv. Gal. Diesel/Hr	Equiv. Gal. Diesel/Ton of Mix
Asphalt Heating and Storage	6,000	960,000	6.9	0.046
Lcader	4,380	657,000	4.7	0.031
Cold Bins, Vibrators, Belt Feeders	100	15,000	0.1	0.001
Cold Feed Belt Conveyor	250	37,500	0.3	0.002
Cold Feed Total	4,730	710,000	5.1	0.034
Dryer Drive Motor	1,260	188,000	1.3	0.009
Dryer Fuel Pump Blower	1,460	218,000	1.5	0.010
Dryer Exhaust Fan	1,260	189,000	1.4	0.009
Dryer Secondary Dust Collector	800	120,000	0.9	0.006
Dryer Total	4,780	715,000	5.1	0.034
Mixing Plant Hot Elevator	350	53,000	0.4	0.003
Mixing Plant Screening	455	68,300	0.5	0.003
Mixing Plant Asphalt Pump	250	37,500	0.3	0.002
Mixing Plant Mineral Filler Elevator	200	30,000	0.2	0.001
Mixing Plant Pugmill	2,070	310,000	2.2	0.015
Mixing Plant Compressor (Discharge)	200	30,000	0.2	0.001
Mixing Plant Storage Conveyor	400	60,000	0.4	0.003
Mixing Plant Total	3,920	589,000	4.2	0.028
Drying and Heating Aggregate	233,000***	35,000,000	252	1.68
Plant Operation Total	253,000	38,000,000	273	1.82
Paving Machine	4,170	625,000	4.5	0.030
Rollers--3	12,500	1,880,000	13.5	0.090
Spreading and Compaction Total	16,700	2,500,000	18.02	0.120
Drying and Heating Aggregate	278,000 (9)	41,700,000	300	2.00
Drying and Heating Aggregate	278,000 (10)	41,700,000	300	2.00
Drying and Heating Aggregate	327,000****	49,000,000	353	2.35
Plant Operation (excluding drying)				
Lay and Compact	41,700 (9)	6,260,000	45	0.300
Plant Operation (excluding drying)				
Lay and Compact	40,910	6,140,000	44.1	0.30

*Operating at 67 percent rated power.

**Operating at 150 Ton/Hr (907 kg/hr).

***5% moisture removed and raise temperature to 300°F (148°C) for a mix which contains 94% by wt. of aggregate.

****Unpublished Illinois source stated in Ref. 14.

After reference 14 except where noted.

Metric Conversion:

1 Btu/Ton = 1.164 J/kg   1 Btu/Hr = 1055 J/hr

1 Gal/Hr = 3.785 l/hr   1 Gal/Ton = 4.173 l/1000 kg

Table 10. Energy Associated with Portland Cement Concrete Production.

Operation	Energy Requirements			
	Btu/Ton Ton Of Mix	Btu/Yd^3 Of Mix*	Equivalent Gal. of Diesel Per Ton of Mix	Equivalent Gal. of Diesel Per Yd^3 of Mix
Loader	4,380	8,870	0.032	0.065
Conveyor	270	550	0.001	0.003
Mixing and Other Plant Operations	1,770	3,580	0.013	0.026
Total Plant Operation	6,420	13,000	0.046	0.094
Placing, Consolidation and Finishing	2,590	5,240	0.019	0.038

*150 Lb/Ft^3 (2400 kg/m^3) assumed unit weight (after Reference 1)

Metric Conversion:

1 Btu/Ton = 1.164 J/kg

1 Btu/yd^3 = 1.381 J/m^3

1 Gal/Ton = 0.00417 l/kg

1 Gal/Yd^3 = 4.951 l/m^3

Table 11. Energy Associated with Asphalt Plant Operations.

	Btu/Ton of Mixture Produced	
Equipment Item	Batch Plant	Dryer-Drum Plant
Asphalt Storage	6,400	6,400
Cold Feed	4,730	4,730
Dryer and Exhaust	4,770	4,770
Mixing plant	3,920	650
Total	19,820*	16,550*

*These totals do not include the energy required to dry and heat the aggregate which is approximately 250,000 Btu per ton of aggregate.

From Reference 7.

Table 12. Energy Consumption for Pavement Materials In-Place*.

Material	Energy Requirement			Ref.
	Btu/Ton	Btu/Yd3	Btu/Yd2In.	
	512,000	1,000,000	27,000	(1)
Asphalt Concrete	533,000	1,040,000	29,000	(11)
PCC-Jointed Non-Reinforced	990,000	2,000,000	55,500	(12)
PCC-Jointed Non-Reinforced	1,210,000	2,450,000	68,000	(1)
PCC-Jointed Reinforced	1,390,000	2,820,000	78,400	(1)
PCC-Continuously Reinforced	1,620,000	3,280,000	91,110	(1)
Slurry Seal			1,340**	(13)
Chip Seal - Emulsion and Crushed Stone			3,950**	(1)
Fog Seal			470**	(1)
Crushed Stone Base	236,000	414,000	11,500	(1)
	218,000	382,000	10,000	(8)
Emulsified Asphalt Base	300,000	562,000	15,600	(1)
Cement-Stabilized Base	600,000	1,100,000	30,500	
Polyhydrate - Fly Ash Base	325,000	605,000	16,800	
Cement-Treated Subgrade	526,000	852,000	23,700	(14)
Lime - Fly Ash	385,000	720,000	20,000	
Lime-Stabilized Subgrade	526,000	852,000	23,700	

(Continued)

Table 12. (Continued)

*Includes energy associated with manufacturing, mixing, hauling, placing, and compacting.

**These treatments are not 1 in. in thickness.

Metric Conversion:

1 Btu/Ton = 1.164 J/kg

1 Btu/Yd^3 = 1.381

1 $Btu/Yd^2 in.$ = 497 $J/m^2 cm$

1 in. = 2.54 cm

Table 13. Energy Requirements for Miscellaneous Construction Operations.

Operation*	Energy Requirement				
				Equivalent Gallons of Diesel Per	
	Btu/Gal	Btu/Ton	Btu/Yd^3	Ton	Yd^3
Spreading and Compaction Granular and Stabilized Based		17,000	30,980	0.122	0.223
Travel Plant Mixing in Windrow		3,000	5,470	0.022	0.039
Blade Mixing		7,820	14,250	0.056	0.103
Central Plant Mixing of Stabilized Base		6,890	12,550	0.050	0.090
Excavation - Earth		39,890	59,100 (11)	0.286	
Excavation - Rock		35,500	76,700 (11)		
Excavation - Other		39,100	68,700 (11)		
Asphalt Distribution, Asphalt Cement	590				
Asphalt Distribution, Cutback Asphalt	445				
Asphalt Distribution, Emulsified Asphalt	145				
Aggregate Spreading for Seal Coats	9.4**				
Rolling Cold Asphalt Mixes	120***				

*135 lb/ft^3 (2160 kg/m^3) assumed unit weight except for excavation items.

**9.4 Btu/Yd^2

***120 Btu/Yd^2 in.

(Continued)

Table 13. (Continued)

Metric Conversion:

1 Btu/Gal = 278.7 J/l

1 Btu/Ton = 1.162 J/kg

1 Btu/Yd^3 = 1.381 J/m^3

1 Ton = 907 kg

1 Yd^3 = 0.764 J/m^3

1 in. = 2.54 cm

After Reference 1 except where noted.

Table 14. Energy Associated With Asphalt Distribution Operations.

	Asphalt Cement	Cutback Asphalt	Emulsified Asphalt
Heating Asphalt	545 Btu/Gal	400 Btu/Gal	100 Btu/Gal
Spraying Asphalt	27 Btu/Gal	27 Btu/Gal	27 Btu/Gal
Distributor Truck	17 Btu/Gal	17 Btu/Gal	17 Btu/Gal
Total	589 Btu/Gal	444 Btu/Gal	144 Btu/Gal

After Reference 7.

Table 15. Representative Energy Requirements for Maintenance and Rehabilitation Activities.

Maintenance Activity	Energy/Unit	Energy Requirements: Btu/Yd^2 of Area Treated	Btu/Yd^2	Btu/Lane Mi*	Btu/Yd^2	Percent of Total Pavement Area Treated & Others Assumptions
Fog Seal -	10,500 Btu/Gal (16)	1,050		3,700,000	525	50 percent
Partial Width	12,100 Btu/Gal (17)	1,120		3,950,000	560	
Fog Seal -	6,850,000 Btu/Lane mi (16)	970		6,850,000	970	100 percent
Full Width	3,300,000 Btu/Lane mi (1)	470		3,300,000	470	
Chip Seal -	537,000 Btu/Yd^2 (16)	8,200		8,660,000	1,230	
Partial	1,100,000 Btu/Yd^2 (18)	9,210		9,725,000	1,380	
	1,000,000 Btu/Yd^2 (17)	6,000		6,300,000	900	
	1,630,000 Btu/Yd^2 (17)	7,500		7,930,000	1,130	
	1,160,000 Btu/Yd^2 (17)	8,100		8,600,000	1,210	
Chip Seal -	30,700,000 Btu/Lane mi (16)	4,360		30,700,000	4,360	100 percent
Full Width	27,800,000 Btu/Lane mi (1)	3,950		27,800,000	3,950	
Surface Patch -	1,700,000 Btu/Yd^3 (18)	45,000	45,000	8,000,000	1,140	2.5 percent
Hand Method	3,210,000 Btu/Yd^3 (17)	89,300	89,300	15,700,000	2,260	1 in. thick
Surface Patch -	880,000 Btu/Yd^3 (17)	24,500	24,500	17,200,000	2,450	10 percent
Machine Method	1,070,000 Btu/Yd^3 (16)	29,800	29,500	21,000,000	2,990	1 in. thick
	1,190,000 Btu/Yd^3 (18)	33,085	33,085	23,300,000	3,300	
Digout and Repair	1,600,000 Btu/Yd^3 (16)	178,000	44,460	25,000,000	3,560	2 percent
Hand Method						4 in. thick
Digout and Repair	1,120,000 Btu/Yd^3 (16)	187,000	31,200	65,800,000	9,35	5 percent
Machine Method	810,000 Btu/Yd^3 (17)	135,000	22,500	47,500,000	6,750	6 in. thick
Crack Pouring	32,000 Btu/Gal (16)			8,500,000	1,220	250 lin. ft.
	60,670 Btu/Gal (17)			16,020,000	2,280	per station
	33,500 Btu/Gal (19)			8,700,000	1,230	50 lin. ft/gal
	29,300 Btu/Gal (18)			7,600,000	1,080	
Slurry Seal	9,400,000 Btu/Lane mi (13)	1,340		9,400,000	1,340	100 percent
Asphalt Concrete	512,000 Btu/Ton (1)	55,600	27,800	391,000,000	55,600	100 percent
Overlay	533,000 Btu/Ton (11)	57,800	28,900	407,000,000	57,800	2 in. thick

*Energy requirements for Yd^2 of total pavement surface maintained. For example, surface patching by the hand method may have been applied over only 5 percent to total pavement surface area, yet energy reported is for the pavement area maintained on one lane mi. of pavement.

(25) Indicates reference on which data is based.

Metric Conversion: 1 Btu/Gal = 278.7 J/l; 1 Btu/Mi = 656.1 J/km; 1 Btu/Yd^3 = 1.381 J/m^3

1 Btu/Gal = 1.164 J/kg; 1 Btu/Yd^2 = 1263 J/m^2; 1 Btu/Yd^{2}in = 497 J/m^{2}cm

1 in. = 2.54; 1 ft. = .305 m

Table 16. Representative Energy Requirements for Pavement Recycling Operations.

Recycling Method	Btu/Yd^2	Thickness of Treatment, in. of Depth
Heater-Planer	10,000 - 20,000	3/4
Heater-Scarify	10,000 - 20,000	3/4
Hot-Milling	2,000 - 4,000	1
Cold-Milling	1,000 - 2,500	1
In-Place Recycling	15,000 - 20,000	1
Hot Central Plant Recycling	20,000 - 25,000	1

After Reference 15.

1 Btu/Yd^3 = 1381 J/m^3

Table 17. Pavement Rehabilitation Alternatives Defined.

Plan 1:	Two-inch asphalt concrete overlay with maintenance on a 7-year cycle (asphalt concrete $25.00 per ton).
Plan 2:	Chip seal plus 2-inch asphalt concrete overlay with maintenance (chip seal $0.55 per square yard, asphalt concrete $25.00 per ton).
Plan 3:	Fabric reinforcement plus 2-inch asphalt concrete overlay with maintenance (fabric reinforcement $1.25 per square yard, asphalt concrete $25.00 per ton).
Plan 4:	Recycle existing 4 inches of material and blend a selected aggregate into recycled mixture. A 2-inch overlay is schedule after 5 years (recycling at $20.00 per ton and overlay at $25.00 per ton).
Plan 5:	Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance (recycling $16.00 per ton, asphalt concrete $25.00 per ton).
Plan 6:	Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance which includes a 2-inch overlay (recycling $16.00 per ton, asphalt concrete $25.00 per ton).
Plan 7:	Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance (recycling $20.00 per ton, asphalt concrete $25.00 per ton).
Plan 8:	Delay recycling 4 years and then recycle and add 2 inches of asphalt concrete overlay with maintenance (recycling $16.00 per ton, asphalt concrete $25.00 per ton).
Plan 9:	Heater-scarify to a depth of 1 to 1.5 inch and 2 inches of asphalt concrete overlay with maintenance (heater-scarification $0.90 per square yard, asphalt concrete $25.00 per ton).
Plan 10:	Asphalt-rubber interlayer and 2 inches of asphalt concrete overlay with maintenance (asphalt-rubber interlayer $1.25 per square yard, asphalt concrete $25.00 per ton).

Table 18. Rehabilitation Alternatives Cost Schedule*

Year	Plan 1 2" A.C. Overlay	Plan 2 Seal Coat +2" A.C. Overlay	Plan 3 Fabric Reinforcement +2" A.C. Overlay	Plan 4 Recycle	Plan 5 Recycle +2" A.C. Overlay	Plan 6 Recycle +2" A.C. Overlay	Plan 7 Recycle +2" A.C. Overlay	Plan 8 Recycle +2" A.C. Overlay	Plan 9 Heater-Scarify +2" A.C. Overlay	Plan 10 Asphalt Rubber Interlayer +2" A.C. Overlay
1980	2.50	3.05	3.75	4.00	5.70	5.70	6.50	0.15	3.40	3.75
1981								0.15		
1982								0.15		
1983	0.08							0.15		
1984	0.13	0.08	0.08					6.50	0.08	0.08
1985	0.15	0.13		2.50						
1986	0.15	0.15	0.13						0.13	0.13
1987	2.50	0.15								
1988		0.15	0.15		0.08	0.08	0.08		0.15	0.15
1989		2.50								
1990	0.08		2.50		0.13	0.13	0.13		2.50	2.50
1991	0.13			0.08				0.08		
1992	0.15	0.08			0.15	0.15	0.15			
1993	0.15	0.13	0.08	0.13				0.13	0.08	0.08
1994	2.50	0.15	0.13		0.15	2.50	0.15		0.13	0.13
1995		0.15	0.15	0.15				0.15	0.15	0.15
1996		3.05	0.15		0.15		0.15		0.15	0.15
1997	0.08		0.15	0.15				0.15	0.15	0.15
1998	0.13		0.15		0.15	0.08	0.15		0.15	0.15
1999	0.15		0.15	0.15				0.15	0.15	0.15
2000	0.15	0.08	0.15		0.15	0.13	0.15		0.15	0.15

*Numbers represent costs per square yard.

Table 19. Energy Associated with Plan 1 and Plan 2 Alternative Pavements.

Year	Btu's Per Yd^2	
		Plan 7
Initial Energy	57,800	177,400
1		
2		
3	1,000	
4	2,000	
5	3,000	
6	3,000	
7	57,800	
8		1,000
9		
10	1,000	2,000
11	2,000	
12	3,000	3,000
13	3,000	
14	57,800	3,000
15		
16		3,000
17	1,000	
18	2,000	3,000
19	3,000	
20	3,000	3,000
Total	200,000	195,400

1 Btu = 1055 $1\ Yd^2 = 8.36 \times 10^{-1}\ m^2$

Table 20. Energy Associated with Plan 1 and Plan 2 Alternative Pavements.

	Btu's Per Yd^2	
Year	Plan 1	Plan 7
Initial Energy		
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
Total		

1 Btu = 1055 J

1 $yd^2 = 8.36 \times 10^{-1}$ m^2

Table 21. Cost and Energy Summary

		Energy, Btu/Sq. Yd.		Cost, Dollars/Sq. Yd.		
					20 Year Life*	
Plan No.	Method	Initial	20 Year Life	Initial	0 Percent	8 Percent
1	2" AC Overlay	57,800	200,000	2.50	9.03	5.50
2	Seal Coat + 2" AC Overlay	61,700	203,000	3.05	9.85	5.80
3	Fabric + 2" AC Overlay	60,000	145,000	3.75	7.72	5.44
4	Recycle	119,600	190,000	4.00	7.16	5.91
5	Recycle + 2" AC Overlay	177,400	195,000	5.70	6.66	6.03
6	Recycle + 2" AC Overlay	177,400	244,000	5.70	8.77	6.76
7	Recycle + 2" AC Overlay	177,400	195,000	6.50	7.46	6.83
8	Recycle + 2" AC Overlay	2,200	201,000	0.15	7.76	5.52
9	Heater-Scarify + 2" AC Overlay	74,800	160,000	3.40	7.37	5.09
10	Asphalt Rubber Inter-layer + 2" AC Overlay	64,000	149,000	3.75	7.72	5.44

*Equal annual costs assuming 0 and 8 percent rate of return.