NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **85**

ENERGY INVOLVED IN CONSTRUCTION MATERIALS AND PROCEDURES

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ENERGY INVOLVED IN CONSTRUCTION MATERIALS AND PROCEDURES

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. DECEMBER 1981

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The Transportation Research Board evolved from the 54-year-old Highway Research Board. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society.

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of special interest to highway administrators, planners, materials engineers, and others concerned with energy consumed in the production, transportation, and placement of materials for highway construction and maintenance. Potential opportunities for energy conservation in construction and maintenance activities are presented.

Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems. Syntheses from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

Energy is involved in the production of construction materials and also in their transportation and placement. This report of the Transportation Research Board includes information on estimating the energy requirements for highway construction and maintenance. Opportunities for conservation are presented, and the uncertain nature of some estimates of energy requirements is discussed.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Paul E. Irick, Assistant Director for Special Technical Activities Division. The Principal Investigators responsible for conduct of the synthesis were Thomas L. Copas and Herbert A. Pennock, Special Projects Engineers. This synthesis was edited by Nancy A. Ackerman.

Special appreciation is expressed to Woodrow J. Halstead, Charlottesville, Virginia, who was responsible for the collection of data and the preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Douglas A. Bernard, Chief, Demonstration Projects Division, Federal Highway Administration; Raymond R. Crowe, Director of Technical Services, American Road and Transportation Builders Association; Lacey A. Glascock, Traffic and Programs Engineer, Louisiana Department of Transportation and Development; Thomas Larkin, Highway Engineer, Office of Development, Federal Highway Administration; William B. Ledbetter, Research Engineer, Texas Transportation Institute, Texas A & M University; and Frank Nichols, Vice President of Engineering, National Crushed Stone Association.

William G. Gunderman, Engineer of Materials and Construction, Transportation Research Board, assisted the Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

ENERGY INVOLVED IN CONSTRUCTION MATERIALS AND PROCEDURES

SUMMARY

This report reviews various published energy requirements for highway construction and maintenance, including the energy requirements for processing the materials and the fuel used in hauling and for construction equipment. Essentially all available data are estimates, usually based on averages for processes or materials that may vary significantly, depending on the circumstances and operating conditions. In most cases, subjective assumptions were made concerning process and equipment operation efficiencies that also may vary significantly among projects.

Although energy estimates are useful as a means of obtaining an overall concept of energy requirements for construction and maintenance of highways, estimates of the expected energy use on a specific project based on the reported factors are subject to large errors. The report emphasizes that decisions concerning the use of alternative types of materials for highway construction and maintenance should be based on technological considerations, safety, and the cost effectiveness of alternatives rather than on uncertain estimates of energy requirements.

The relative roles of construction energy, transport energy, processing energy, and calorific energy are discussed and are illustrated by computations of estimated requirements by different types of base courses and surfaces. The potential opportunities for energy conservation in various highway construction and maintenance activities are included.

It is recommended that each of the four categories of energy discussed—transportation, construction, processing, and calorific—be computed separately and that each be taken into consideration in any decision concerning overall energy requirements for a given highway construction or maintenance project. The escalating costs of fuel required for transporting materials and operating construction equipment most directly affect short-term costs and changes in costs of highway projects. Processing energy can be derived from alternative sources and costs for different materials will be affected by the criticality of the source of the energy used as well as the amount. Calorific energy is inherent in the materials and affects costs only to the extent that the raw material involved could have been marketed as a fuel.

CHAPTER ONE

INTRODUCTION

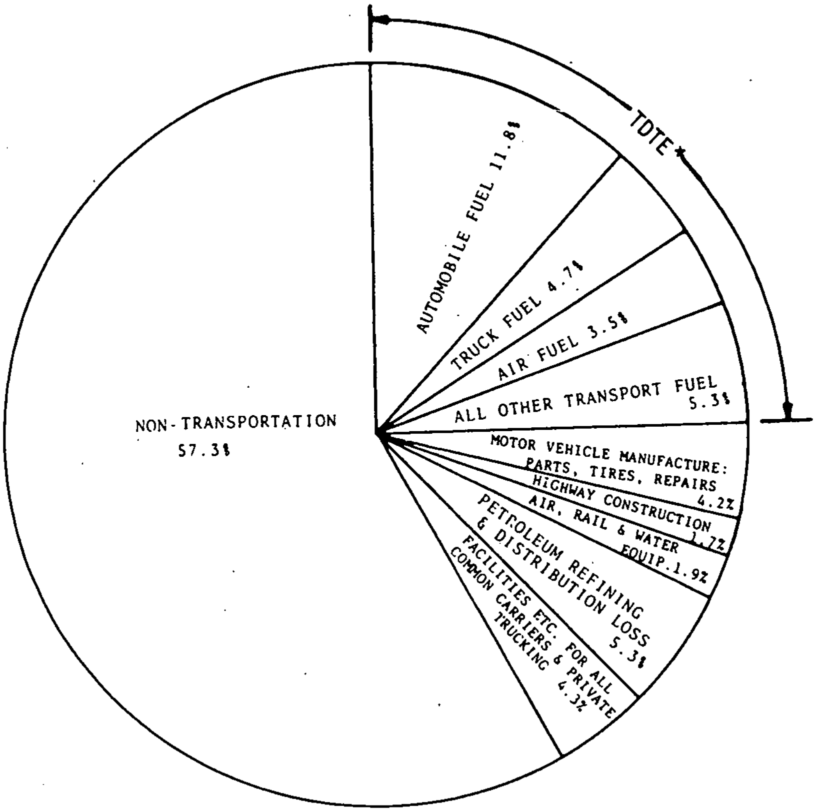
Since the beginning of the oil embargo in 1973, the problem of assuring an adequate supply of energy to fuel technology and maintain quality of life has been a major concern. In the United States, particularly, the changes in the supply and the rising cost of energy have affected all aspects of society.

An approach to the problem of maintaining an adequate supply of energy is to find solutions to each of the component problems. Alternative and new sources of energy, such as gasohol, liquefied coal, solar, and biomass, are integral parts of the solution as are conservation through elimination of waste, reuse of salvaged materials, and more efficient procedures in the use of fossil fuels.

Energy for transportation is a major part of the total energy use in the United States. An analysis of the total 1967 energy consumption showed the total energy requirement of the transportation sector for that year to be 58.265 quads (1 quad = 10^{15} Btu) (*1*). Highway construction was reported to be 1.7 percent of the total (Figure 1), or 0.99 quad. No specific estimates for the energy used in highway construction after 1967 could be located.

The total expenditures for highway construction doubled between 1967 and 1977. During this period the price index for highway construction increased to 264.9 (*2*). The volume of work in highway construction was reduced by about 24 percent. Maintenance and rehabilitation, however, increased between 1967 and 1977. Thus, it is reasonable to assume that the energy used annually for highway construction and maintenance remains at about 1 quad or 10^{15} Btu. This is equivalent to about 7.2×10^9 gal of diesel fuel each year.

Although 7.2×10^9 gal of diesel fuel per year is a relatively modest proportion of the total annual energy requirement of the United States, it represents a large amount of energy in absolute volume. Thus conservation measures are important.



*TDTE - Total Direct Transportation Energy

FIGURE 1 Components of transportation energy as a percentage of total energy used (*1*).

Conservation within the highway construction industry is especially important in controlling costs. Soaring costs of highway construction and maintenance, coupled with reduced revenues, challenge the efficiency of highway transportation. Extreme curtailment of needed highway construction and maintenance or the acceptance of lower quality in order to conserve energy or reduce first costs could increase the overall energy used. Additional fuel would be burned by vehicles delayed by traffic jams and lifetime costs would be increased because of more frequent and costly maintenance activities.

To realize maximum efficiency in energy use in highway construction, both the relative energy requirements for highway construction operations and the amount of energy involved in the processing or manufacture of various construction materials must be determined. Although various publications provide estimates of such energy factors, these estimates are often based on subjective assumptions and sometimes estimates for the same activity are not in agreement. Additionally, a literature survey reveals that references can be traced to a single source where the origin of the data is not given.

This synthesis was undertaken to (a) collect the available information on the factors of concern in highway construction, and (b) establish, where possible, the basis for various estimates so that a range of values or a best value could be established for comparing energy use for different materials and procedures. The study also seeks to identify those areas where additional data are required to provide suitable guides to contract adjustments or to suggest less energy-intensive alternatives in the event of new shortages of energy and highway construction materials.

CHAPTER TWO

ENERGY UNITS, DEFINITIONS, AND CATEGORIES

ENERGY UNITS

In the U.S. customary system of measurement, the basic unit of energy consumption is the Btu. A Btu is the amount of energy required to raise the temperature of 1 lb of water 1° F. The counterpart of the Btu in the metric system is the small calorie. It is the amount of heat required to raise the temperature of 1 g of water 1° C. The calorie unit used in relation to food and nutrition is 1,000 small calories.

The basic unit of energy in the International System of Units (SI) is the joule (J). It is defined as the work done when the point of application of a force of 1 newton is displaced a distance of 1 m in the direction of the force (N·m). A newton is the force that when applied to a body having a mass of 1 kg gives it an acceleration of 1 m per sec per sec ($kg \cdot m/s^2$) (*3*). One Btu is equal to 1055 J and 1 small calorie is equal to 4.186 J. See Appendix A for additional conversion factors.

All units in this report are expressed in the U.S. customary system and energy is expressed as Btu per unit or converted to the equivalent gallons of diesel fuel, using the factor of 139,000 Btu/gal.

The total energy involved in a construction procedure is only a partial measure of the energy impact on the consumption of nonrenewable energy resources. Such impact varies in accordance with its source, i.e., petroleum, natural gas, coal, nuclear fission, or solar. For example, a process using energy produced from solar sources might have negligible effect on the consumption of nonrenewable resources even though a large total amount of energy is involved. Costs per unit of energy can vary significantly depending on its origin, the distance it is moved to the point of use, and other factors.

ENERGY ASSOCIATED WITH MATERIALS

Calorific energy is the characteristic of primary concern for materials used as fuels. It is the heat energy released when the product is completely burned. The energy required to refine, mine, or otherwise prepared such fuels for use is not included in calculating the amount of heat available in fuels.

Processing energy—the amount of fuel and/or electrical energy required to provide a unit of the material in a usable form—is the principal energy consideration for processed and manufactured materials.

Differences exist as to whether the calorific energy of construction materials that are combustible should be included as part of the processing energy. This consideration is appropriate when initially a choice exists as to whether the parent materials would be used as a fuel or as a construction product. This is the case for many of the residues from refining petroleum, which can be marketed either as an asphalt cement or as a residual fuel.

The Asphalt Institute considers asphalt a construction material that is removed from petroleum by refining and does not include the calorific energy as part of the processing energy (*4*). The center for Advanced Computation of the University of Illinois uses the term *embodied energy* to represent all energy expended in preparing a construction material for use (*5*). This includes the energy used to transport the material from its origin to the point of use, and the energy expended to store the material prior to use.

ELECTRICAL ENERGY

With electrical energy, one form of energy is converted to another primarily in order to transport the energy and make it available for use in a convenient form. One kilowatt-hour (kWh) is equivalent to 3,412 Btu. However, the conversion of fuel at the power plant to electricity is only about 31 to 33 percent efficient (*4*); 65 percent of the heat energy of fuel is lost during the generation of electricity (*6*). An additional 3 percent is lost in transmission (*6*). Therefore, between 10,000 and 11,000 Btu of input energy is required to provide 1 kWh of electrical energy at the point of use. In this report, the input value of 11,000 Btu (based on 32 percent efficiency and rounded to the nearest 1,000 Btu) is used as the conversion factor for electrical power. Thus, 1 kWh of electricity is equivalent to 0.079 gal of diesel fuel or 0.088 gal of gasoline (based on 125,000 Btu/gal of gasoline).

The initial source of energy selected to generate electricity affects significantly the consumption of natural resources. Of the 24.807 quads of energy used by electrical generating utilities in 1980, 12.117 quads were obtained from coal, 3.791 quads from natural gas, 2.938 quads from petroleum, and the balance from nuclear, hydroelectric, and other sources such as geothermal or wood and wastes (*6*). Thus, on a national basis, petroleum furnished only 12 percent of the energy consumed to generate electricity. However, in specific locations, the availability of different fuels affects the proportion of electrical energy obtained from petroleum. Thus, the "criticality" of its use with respect to petroleum supplies would vary.

POWER AND WORK

One horsepower (hp) (550 ft-lb/s) is equal to 0.7457 kW and 1 hp-hr is equivalent to 2,544 Btu (theoretical). The burning of fuel in diesel engines to produce power is about 46 percent efficient (*4*). Thus, about 0.04 gal of diesel fuel is required to produce 1 brake horsepower-hour (hp-hr) (2,544/0.46/139,000). This is equivalent to 5,530 Btu/hp-hr.

Inasmuch as gasoline engines are about 34 percent efficient (*4*), it requires 0.06 gal of gasoline to generate 1 brake hp-hr (2,544/0.34/125,000). This is equivalent to 7,482 Btu/hp-hr.

The assumptions made concerning efficiencies in estimating energy use are subjective and should be based on the purposes for which estimates are being made. When total energy availability for all purposes at the national level is being considered, a measure is needed of the input energy required to provide the useful power or fuel at the point of its use. In this case, the total energy represents the sum of the calorific energy and the processing energy. If energy equivalencies of different fuels are of primary concern, the calorific energy of the fuels at the time of use should be compared.

Energy requirements for highway construction considered in this report include two additional categories: (a) the energy used as fuel for transporting component materials and mixtures for pavements and other transportation facilities, and (b) the energy used as fuel in equipment in typical highway construction and maintenance operations, including recycling.

Many indirect energy uses are also associated with highway construction and maintenance. These energy uses are important considerations for overall planning for alternative modes of transportation and any assessment of overall energy demands of the economy. Such indirect energy uses include that required for (a) manufacture and maintenance or repair of construction equipment, (b) transport of personnel to and from job sites, and (c) expenditures of energy caused by delays due to construction and maintenance operations. However, because this report is primarily concerned with energy involved in construction materials and processes, these indirect energy uses will not be discussed.

DEFINITIONS

The various types and categories of energy discussed in this report are defined as follows:

Calorific energy (E_h). The heat energy released when a fuel or other product is completely burned.

Processing energy (E_p). The energy required to manufacture or otherwise process a unit of material. Such materials will usually be used as components of a structure or unit of construction. In this report calorific energy is not considered a part of the processing energy.

Transport (hauling) energy (E_t). The energy used as fuel for transporting materials from the point of their origin or manufacture to the point of their use.

Construction energy (E_c). The energy used as fuel (including electrical energy) in operating construction equipment. For highway construction this includes mixing plants, conveyors, distributors, rollers, etc. In this report, 1 kWh of electrical energy is considered the equivalent of 11,000 Btu (input requirement).

CHAPTER THREE

ENERGY FOR MATERIALS, PRODUCTION, AND PROCESSING

This chapter deals with the energy factors and energy relations of specific materials. Published factors may differ because of assumptions of different efficiencies for conversion processes or different averages for the same type of material. To the extent possible, the basis for each factor is given. Much of the data reported is based on values obtained between 1972 and 1975. Efforts to improve efficiency in various industries and future changes in efficiencies of processes may result in significant changes.

For uniformity in this report, all energy factors involving assumptions and approximate estimates are rounded to three significant digits. However, the precision of general estimates made on the basis of such factors will rarely be better than ± 10 percent and in many cases will be less precise.

PETROLEUM AND PETROLEUM DISTILLATES

The energy in a barrel of petroleum varies depending on its source; 5.8×10^6 Btu/barrel is an average used in the literature (*6*). This average represents the calorific energy available in crude petroleum and is greater than the usable energy after refining. Refining of different crude oils requires varying amounts of energy (refinery energy) depending on the refining process and characteristics of the crude. In the average yield of products from refining a barrel of crude oil, shortages and miscellaneous products account for 6.8 percent (*7*); see Figure 2.

Discussions with several representatives of major oil companies indicate that a fixed percentage of refining energy cannot be given, but the net useful energy of a barrel of petroleum is usually about 90 to 92 percent of the calorific energy contained in the original crude oil. Although more refining energy is required for cracking or reforming techniques, some of the additional energy used is available in the finished product. From the standpoint of automotive fuels, Lawrence et al. (*8*) indicated that an average of 8 percent of the input energy was required in refining.

The calorific energy of various petroleum fuels given in Table 1 is consistent with other published values (*6*). The factors are based on calorimeter tests for different distillates and extrapolations based on the elemental analysis and specific gravities of the distillates. The calorific energy is a measure of the energy released when the product is completely burned. If the refining energy is equally prorated for all materials, a value 8 to 10 percent higher than those shown in Table 1 would approximate the total energy [calorific energy (E_h) plus processing energy (E_p)] of the refined product. The useful work obtained from a gallon of fuel depends on the type of use and the efficiency of the motor vehicle in which it is used.

PAVING ASPHALT

The amount of energy attributed to the manufacture and processing of paving asphalt is a matter of definition and opinion. Asphalt is reported to contain 6.636×10^6 Btu/barrel (bbl) or 158,000 Btu/gal (*6*). Under the definition being used in this report, these values represent the calorific en-

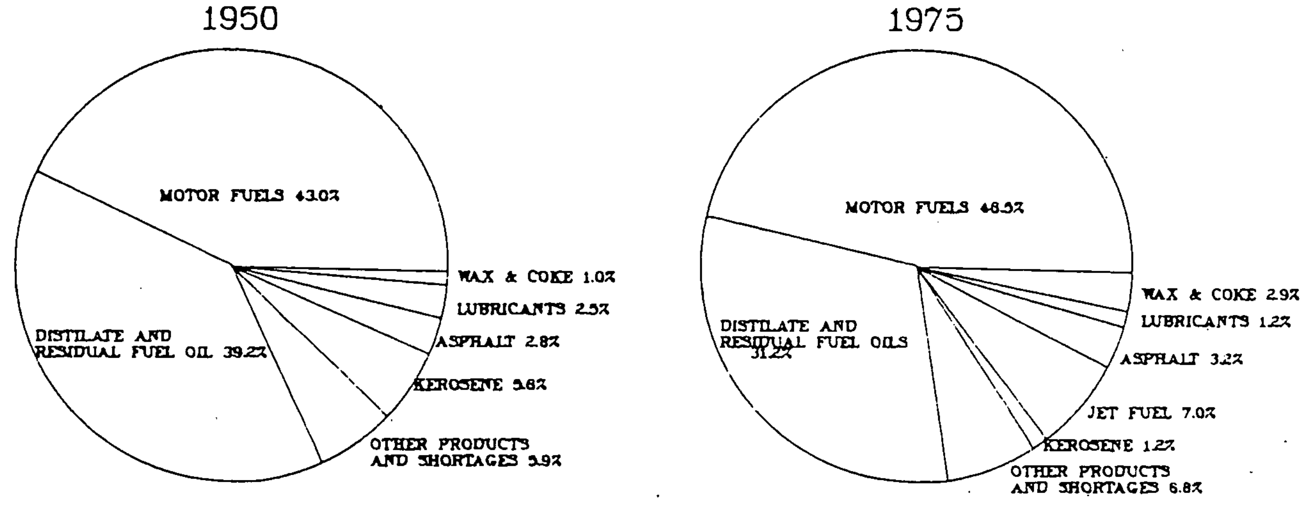


FIGURE 2 Yield from a barrel of crude oil (7).

TABLE 1
CALORIFIC ENERGY IN PETROLEUM FUELS[a]

Fuel	Energy (Btu/gal)
Gasoline	125,000
Kerosene	135,000
Fuel Oil No. 1 (API 42)	135,000
Fuel Oil No. 2 (API 35, diesel)	139,000
Fuel Oil No. 3 (API 28)	143,000
Fuel Oil No. 4 (API 20)	148,500
Fuel Oil No. 5 (API 14)	152,000
Fuel Oil No. 6 (API 10)	154,500

[a] Based on data from the Asphalt Institute (4). Calorific energy is the heat released when the product is completely burned.

ergy (E_h). The Asphalt Institute considers paving asphalt a "building material," and defines the energy for asphalt cement as the energy needed to heat the asphalt during refining plus an added amount for further processing and handling. This definition does not include the calorific energy (E_h) in the asphalt and thus is the same as the definition for processing energy (E_p) as used in this synthesis. The amount of energy required to heat asphalt during refining has been reported to range from less than 10,000 to more than 75,000 Btu (*4*). The energy used in processing and handling is reported to vary from 36,500 to more than 60,000 Btu. The energy requirement of asphalt, the specific heat of which is 0.5, is reported as 52,500 Btu/bbl, assuming an 80 percent efficiency in the heating of asphalt and an initial temperature of 65°F for crude oil and a temperature of 300°F at discharge and storage. Another 52,500 Btu/bbl is added to obtain the reported figure of 105,000 Btu/bbl and 2,500 Btu/gal (Table 2).

Among the various arguments as to whether the calorific energy (E_h) in the asphalt should be considered a part of the energy requirement for highway construction, is the notion that, inasmuch as the calorific energy in the asphalt was included in the original crude petroleum, it should be counted as a part of the energy of the finished product (*9, 10*). Fels suggests that the calorific energy in the asphalt of a pavement still exists and that it would be possible to extract it from the road (*11*). Thus, it should not be considered as a part of the total energy used for asphalt paving. However, the energy needed to tear up and remove the pavement would be deducted from the energy available from the asphalt. The energy required to remove the sulfur from the asphalt to make it an environmentally clean fuel must be included in the refining costs (*11*). Because it is unlikely that a pavement would ever be removed for its fuel value, this concept seems less than realistic.

TABLE 2
ENERGY FACTORS FOR PAVING ASPHALT

Processing Energy[a]	2,500	Btu/gal
	105,000	Btu/bbl
	587,000	Btu/ton[b]
Calorific Energy[c]	158,000	Btu/gal
	6,640,000	Btu/bbl
	37,100,000	Btu/ton[b]

[a] Processing energy (E_p) is defined in this report as the energy used in refining. The calorific energy (E_h) in the asphalt is not included in processing energy.

[b] Based on 235 gal/ton; specific gravity of asphalt assumed to be 1.022.

[c] Calorific energy is the heat energy released when the product is completely burned.

Another approach to the evaluation of the energy in paving asphalt would be a determination of the net difference between the usable fuel energy obtained when petroleum is refined to yield paving asphalt as one of the products and the fuel energy obtained when the asphalt is included as a part of the residual fuel oil, or when cracking techniques are used to yield only coke as a residue. However, such net values vary significantly depending on the type of crude oil. In some cases the residue is burnable without special anti-pollution devices and the calorific energy of the asphalt would essentially all be available as usable fuel energy. When cracking techniques are used, the additional net energy contained in the cracked distillates after deducting the additional refining energy would represent an estimate of net fuel energy sacrificed for the sake of making asphalt. Other residues containing appreciable amounts of sulfur could not be burned in land-based power plants without appreciable capital investment in anti-pollution equipment. Specific information on the relative amounts of energy involved in these possible variations could not be found. However, one source indicated that the additional energy involved was only a small percentage of the total and that the total refining energy would still be approximately 10 percent.

Nonetheless, all of these discussions appear to be academic, because refiners decide how to refine their crude petroleum on the basis of the greatest economic return and the need for fuel. The design of a particular refinery affects markedly the range of petroleum characteristics that can be used as a refinery input. For low-sulfur crudes, the option to use the residual as fuel or as an asphalt will be determined primarily by the quality of the asphalt and the relative needs for the products. For high-sulfur crudes, preparation of the residue as a paving material is often more economical because the sulfur can be left in the residue.

It is unlikely that the highway industry will control the decisions on how crude oil should be refined and what products are to be marketed. Consequently, the availability and cost of asphalt, and not its energy content, are major concerns in highway construction. Once the decision has been made to refine the petroleum in a manner that yields paving asphalt as a product, regulatory agencies should not prevent its use based on calculated "energy impact statements."

Decisions on alternative materials to asphalt for highway construction should continue to be made on the basis of engineering requirements and lifetime cost effectiveness. Should critical shortages of asphalt occur, then regulatory decisions on the best use of available materials might be necessary. In summary, processing energy has been used for most calculations for highway construction and calorific energy has been used in most general estimates involving distribution of energy resources.

CUTBACK ASPHALT

The energy reported to be in cutback asphalt varies according to its distillate content and type and how "energy" is defined. Cutbacks may contain up to 50 percent by volume of petroleum distillates. The Asphalt Institute includes the calorific energy (E_h) of the solvents in the processing energy required to produce cutbacks because solvents are added as a substitute for liquefying the asphalt with heat.

In the various grades of cutbacks (Table 3), the solvent for rapid-curing cutbacks is assumed to have a calorific energy (E_h) of 125,000 Btu/gal, that for medium-curing 135,000 Btu/gal, and that for slow-curing 139,000 Btu/gal. The amount of solvent is assumed to be 2 percent less than the maximum allowed by the standard specifications for these products (AASHTO M 81, M 82, and M 141 and ASTM D 2028, D 2027, and D 2026).

The values for processing energy in Table 3 are lower than corresponding values reported by the Asphalt Institute (*4*). The computations of the Asphalt Institute assumed that the maximum amount of solvent was present in each grade, and that 2,500 Btu/gal were added for the processing energy of the asphalt in each gallon of cutback even though a full gallon of asphalt is not used. This compensates, to some extent, for additional processing energy to prepare the cutback. The differences between the values for processing energy given in Table 3 and those reported by the Asphalt Institute (*4*) are not significant for rapid-curing and medium-curing grades. However, the values for slow-curing cutback asphalt presented in Table 3 range from 17 to 40 percent of those reported by the Asphalt Institute (*4*). The Institute used the residue of 100 penetration as the asphalt content of the slow-curing materials and assumed that the difference was distillate corresponding to No. 2 fuel oil. This assumption does not appear to be realistic; a factor based on the amount of distillate obtained in the distillation test appears to provide a better estimate.

TABLE 3
ENERGY FACTORS FOR CUTBACK ASPHALT

Grade	Assumed Solvent (%)	gal/ton	Energy (Btu/gal)	
			Processing[a]	Calorific[b]
Rapid Curing				
70	43	253	55,200	144,000
250	33	249	42,900	147,000
800	23	245	31,700	150,000
3000	18	241	24,600	152,000
Medium Curing				
30	48	256	66,100	147,000
70	43	253	59,500	148,000
250	31	249	43,600	151,000
800	23	245	33,000	153,000
Slow Curing				
70	20	253	29,800	154,000
250	12	249	18,900	156,000
800	7	245	12,000	157,000
3000	2	241	5,200	158,000

[a] These values include the processing energy of the asphalt cement plus the calorific energy of the solvent.

[b] These values include the total calorific energy of the asphalt plus that of the solvent.

TABLE 4
ENERGY FACTORS FOR ANIONIC AND CATIONIC EMULSIONS

Emulsion Type and Grade	Assumed Asphalt (%)	Assumed Distillate (%)	Energy (Btu/gal)	
			Processing	Calorific
Anionic				
RS-1	57	-	1,930	91,000
RS-2	65	-	2,060	103,000
MS-1	57	-	1,930	91,000
MS-2	67	-	2,090	106,000
MS-2h	67	-	2,090	106,000
SS-1	59	-	1,970	94,000
SS-1h	59	-	1,970	94,000
Cationic				
CRS-1	62	2	4,700[a]	101,000
CRS-2	67	2	4,800[a]	109,000
CMS-2	67	6	10,200[a]	115,000
CMS-2h	67	6	10,200[a]	115,000
CSS-1	59	0	2,000	94,000
CSS-1h	59	0	2,000	94,000

[a] Includes calorific energy of distillate.

EMULSIFIED ASPHALT

In calculating the amount of processing energy (E_p) and calorific energy (E_h) in an indicated volume of various types of asphalt emulsions, the asumptions for processing energy given by the Asphalt Institute (*4*) concerning emulsion manufacture were accepted (Table 4). However, the asphalt content of the emulsion is assumed to be 2 percent greater than the minimum allowed by the AASHTO Specifications M 140 and M 208 (ASTM D 977 and D 2397), which is the minimum used by the Institute (*4*). In addition, the energy contained in the distillate for cationic emulsions has been added, assuming the median amount of distillate allowed by the specification (M 208) is present in the emulsion. If the amount of distillate is known, 1350 Btu/gal should be added or subtracted for each percentage point the actual amount deviates from the median value.

The computations of the values in Table 4 assume that 38 Btu is needed to emulsify 1 gal of product. However, 120 Btu of original energy is required to provide this amount of electrical energy.

The processing energy includes the energy needed to heat the water used in the emulsion. This is derived assuming that incoming water at 80° F is heated to 190° F and that the percentage of the emulsion remaining after deducting the percentage of asphalt and emulsifier is the water that must be heated. The processing energy also includes 630 Btu/gal as the energy required to produce the emulsifier. This was calculated assuming that 1 percent (0.084 lb) of emulsifier is added and that 7,500 Btu is required to produce 1 lb of emulsifier (*4*).

The calorific energy for emulsions includes the energy in the base asphalt, the emulsifier, and the distillate, where applicable.

OTHER FUEL FACTORS

The calorific energy (E_h) values of fuels presented in Table 5 are generally consistent with factors published elsewhere (*6*). A U.S. Department of Energy report (*6*) includes information on materials not included in Tables 1 and 5.

TABLE 5
CALORIFIC ENERGY OF FUELS OTHER THAN PETROLEUM PRODUCTS

Fuel	Calorific Energy
Natural gas	1,000 Btu/ft^3
Propane gas	91,000 Btu/gal
Butane gas	100,000 Btu/gal
Coal	11,670 Btu/lb
Petroleum coke	14,470 Btu/lb
Lignite	6,000 - 9,000 Btu/lb

[a] Based on data from NCHRP Report 224 (12).

PORTLAND CEMENT

The amount of energy required to manufacture a unit of portland cement varies appreciably with the process used and the efficiency of each plant operation. Although classed as an "energy-intensive industry," much of the energy can be obtained from coal, and the industry has conducted a vigorous campaign to reduce its use of petroleum-derived energy. Reports on energy conservation in the cement industry (*13–15*) describe the various limitations and problems confronted in improving the energy efficiency within the industry, and give varying estimates of the energy required to manufacture 1 ton of cement.

A 1980 report (*16*) summarizing the industry-wide energy efficiency based on overall 1979 energy use and cement production shows that the 167 cement manufacturing plants reporting had a clinker capacity of 89 x 10^6 tons, which represented more than 99 percent of the total capacity of the U.S. cement industry. In the summary of the total fuel and power used in the manufacture of portand cement (Table 6), the equivalent of 3,412 Btu/kWh was used to convert electrical power instead of the 11,000 Btu/kWh based on energy used. Thus, the totals in Table 6 represent the energy consumed directly by the portland cement industry and do not take into account the energy lost in generating and transmitting the electrical power.

TABLE 6
ENERGY CONSUMPTION IN THE PRODUCTION OF PORTLAND CEMENT ACCORDING TO THE PROCESS OF MANUFACTURE[a]

Energy Type and Production Process	1972	1979	Change (%)
Fuel and Electricity (10^6 Btu/ton)[b]			
All plants	6.745	6.078	-9.9
Wet-process plants	7.169	7.662	-7.1
Dry-process plants	6.072	5.372	-11.5
Fuel (10^6 Btu/ton)			
All plants	6.301	5.593	-11.2
Wet-process plants	6.733	6.200	-7.9
Dry-process plants	5.627	4.869	-13.5
Electricity (kWh/ton)[b]			
All plants	137	149	+8.8
Wet-process plants	129	138	+7.0
Dry-process plants	145	161	+11.0

[a] Based on data from Portland Cement Association (16).

[b] Electrical power converted using a factor of 1 kWh = 3,412 Btu.

Many references dealing with energy use convert electrical energy by using the input factor of about 11,000 Btu/kWh. On this basis the total energy requirements in 1979 for 1 ton of cement by each process and for all plants is given in Table 7.

The U.S. Bureau of Mines reported 5.63×10^6 Btu/ton for fuel in 1977 and 139 kWh electricity/ton (*4*). These convert to 7.16×10^6 Btu/ton on the basis of the 11,000 Btu/kWh. Which factor to use for converting electrical energy is a matter of judgment and would depend somewhat on the purpose of the estimate. However, for most computations dealing with energy use in the highway industry, the conversion factor of 1 kWh = 11,000 Btu is used because this estimate

TABLE 7
ENERGY REQUIRED TO MANUFACTURE PORTLAND CEMENT IN THE UNITED STATES (BASED ON 1979 PRODUCTION)

Process and Energy Type	Energy[a] (10^6 Btu/ton)
All Plants	
Fuel	5.593
Electricity (149 kWh)	1.639
Total	7.232
Wet Process	
Fuel	6.200
Electricity (138 kWh)	1.518
Total	7.718
Dry Process	
Fuel	4.869
Electricity (161 kWh)	1.771
Total	6.640

[a] Based on values given in Table 6 except electrical energy is converted using a factor of 11,000 Btu/kWh instead of 3,412 Btu/kWh.

more nearly indicates the industry's needed share of available energy resources.

Many older cement manufacturing plants in the United States use the wet process, which is shown by the data given in Tables 6 and 7 to be significantly less energy-efficient than the dry process. The cement industry is presently working to replace wet processes with preheater dry-process technology, which reduces energy use. Such replacement will be a long-range procedure because of the large capital investment in present plants and the cost of new ones. The cement industries in Germany and Japan are based almost entirely on the dry process; they report energy use of 3.6 × 10^6 Btu/ton and 3.1 × 10^6 Btu/ton, respectively (*13*). It could not be determined whether electrical power was calculated at 3,412 Btu or 11,000 Btu for these estimates.

Perhaps of even greater significance than the overall reduction of energy use in the cement industry is the shift from petroleum products and natural gas to coal. The use of coal and coke as a fuel for the cement kilns increased from 38.6 percent of the total fossil fuel used in 1972 to 70.7 percent of the total used in 1979 (*16*) (Figure 3). During this period the use of natural gas and petroleum products each was reduced by about 50 percent. Further shifts to coal as a fuel are planned. The use of electrical energy increased about 9 percent between 1972 and 1979. Most of this was attributed to the installation of pollution-abatement and coal-handling equipment. Some plants are also generating some electricity from waste heat.

BLENDED CEMENT

The use of slag and fly ash in the preparation of concrete offers a promising potential for reducing the energy consumption in the concrete industry (*17, 18*). These by-products can be used in two ways: (a) as an ingredient in the manufacture of blended cements, and (b) as an ingredient added to the concrete mixer. A 40 percent reduction in the amount of energy required to manufacture 1 ton of product is possible if blended cements using fly ash are substituted for all portland cement (*19*).

Many practical considerations prevent use of blended cements to this degree; the availability of suitable fly ash close to the cement plant is a controlling factor. The cost and energy required for long hauls of fly ash greatly reduce the potential energy and economic advantages of its use. Reports on the use of fly ash in concrete for highway construction (*20, 21*) indicate that, although permitted by a number of states, the use of either blended cement or fly ash as an admixture in concrete for highway construction has not been extensive. There is, however, a growing interest in such use prompted by a proposal to issue a Guideline for Federal Procurement of Portland Cement Containing Fly Ash by the Environmental Protection Agency (*22*). Generally, economic considerations and the need to dispose of a solid-waste product overshadow the energy conservation factor in this area.

On the assumption that about 20 percent of fly ash is used in the manufacture of most Type IP cements (AASHTO specification M 240 and ASTM specification C 595) now marketed in the United States, a useful figure for the average energy used to manufacture 1 ton of blended cement has been derived. The energy in 1 ton of blended cement is assumed to be equivalent to the energy for 0.75 ton of portland cement plus a small amount of energy required for blending in the fly ash (0.75 × 7.2 × 10^6 Btu = 5.4 × 10^6 Btu plus 10^5 Btu for blending). The total value is 5.5 × 10^6 Btu/ton, which appears to be a reasonable value for the average energy requirement for Type IP blended cement. Other factors could be similarly calculated for blended cements containing different proportions of pozzolans.

AGGREGATE

Crushed Stone

The energy required to produce crushed stone suitable for highway construction varies significantly depending on the type of stone, quarry configuration, amount of overburden, and other factors. Various sources estimate the amount used to be between 36,000 and 70,000 Btu/ton. An average of 56,000 Btu/ton is reported in the literature (*4*).

A survey completed in December 1980 shows that the energy use of 115 quarries operated by members of the

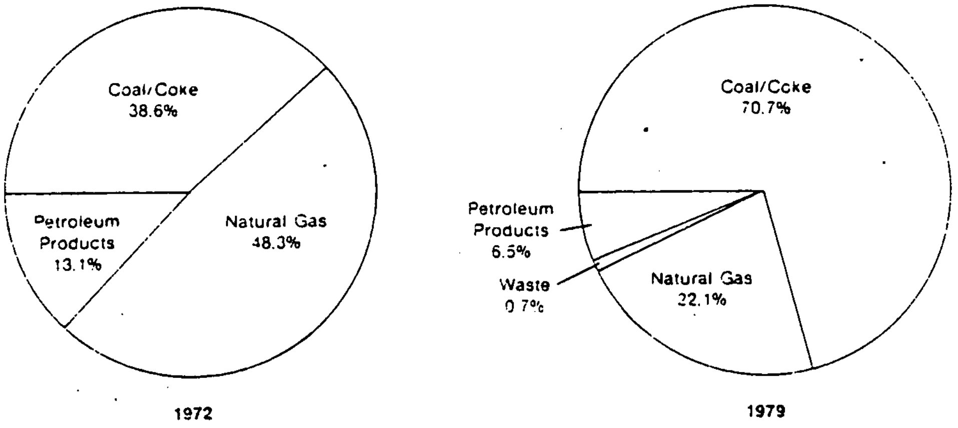


FIGURE 3 Fossil fuel used in manufacturing portland cement (1972 and 1979) (*16*).

National Crushed Stone Association ranged from a minimum of 13,700 Btu/ton to a maximum of 93,100 Btu/ton (*23*). These values were affected by the haul distances involved in handling the stone. The average energy required to produce 1 ton of product for several stone types is summarized in Table 8.

When the input factor of 11,000 Btu/kWh is used, the average energy for processing a ton of aggregate of all types of stone is 58,100 Btu, a value close to the estimates reported in the literature (*4*). For subsequent calculations in this synthesis, the average of 58,100 Btu/ton (equivalent to 0.418 gal of diesel fuel) is used.

Natural and Uncrushed Aggregate (Sand and Gravel)

Based on approximate figures of 2 hp-hr/ton for handling and delivery suggested by the National Sand and Gravel Association, the Asphalt Institute calculates an average of 15,000 Btu/ton for processing natural sands and uncrushed gravels (*4*).

TABLE 8
ENERGY REQUIRED FOR PROCESSING CRUSHED STONE[a,b]

				Total Energy	
Type of Stone	No. of Quarries	Electricity (kWh/ton)	Fuel (gal/ton)	NCSA[c] (Btu/ton)	Adjusted[d] Values (Btu/ton)
Limestone (open pit)	48	3.241	0.195	38,400	62,800
Limestone (underground)	3	3.901	0.198	40,600	70,400
Traprock (open pit)	14	2.901	0.268	35,400	69,200
Granite (open pit)	8	1.738	0.116	30,400	44,000
Total	115[e]	2.830	0.194	35,600	58,100

[a] Based on data from the National Crushed Stone Association (NCSA) (23).

[b] Values are averages of individual quarry reports.

[c] NCSA figures are based on converting electricity by a factor of 3,412 Btu/kWh and converting fuel by a factor of 135,000 Btu/gal.

[d] Adjusted figures are based on converting electricity by a factor of 11,000 Btu/kWh and converting fuel by a factor of 139,000 Btu/gal, which are the factors used in this synthesis.

[e] The total of 115 responses includes types of stone not reported in this table.

TABLE 9
ENERGY FACTORS FOR REINFORCING STEEL IN CONCRETE PAVEMENTS[a]

Bar Designation (No.)	Nominal Diameter (in.)	Unit Weight (lb/ft)	Energy (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

[a] Based on data from the Asphalt Institute (4).

Crushed Gravel

In the absence of specific data, crushed gravel was assumed to require an average of 40,000 Btu/ton (*4*).

REINFORCING STEEL FOR PORTLAND CEMENT CONCRETE PAVEMENT

The energy required to produce steel depends on the type and method of manufacture. The Asphalt Institute suggests an average of 24 × 10^6 Btu/ton as the basis for calculating the energy embodied in the steel used in reinforced portland cement concrete pavements. On this basis, and using a density of 0.283 lb/in.^{3}, the values given in Table 9 (*4*) would apply. Inquiries to the American Institute of Steel Construction indicated that an average value of 30 × 10^6 Btu was used to estimate the industry-wide requirements, but no detailed information on specific types of steel could be obtained.

LIME

The National Lime Association (NLA) estimates that the energy required to produce hydrated lime for road stabilization will range from about 4 × 10^6 to 8.5 × 10^6 Btu/ton, depending on the type and age of the equipment. The value of 4 × 10^6 Btu/ton represents a new plant using the latest technology. The overall average for the industry was estimated to be 7.0 × 10^6 Btu/ton in May 1981 (K. Gutschick, Technical Director, NLA; *personal communication*).

CHAPTER FOUR

FUEL USE IN HAULING AND HIGHWAY CONSTRUCTION AND MAINTENANCE

During the 1973–74 oil embargo a critical shortage of fuel resulted in an allocation program to assure successful bidders on highway projects an adequate supply of fuel to complete the projects. This led to the development of fuel use factors for highway construction (*24*) (Table 10). Stander discusses the significance of these fuel use factors and possible conservation measures that might be taken to reduce fuel use and hold down costs (*25*). The marked differences between the low and high use factors for some operations are not unexpected. This is because of the wide range of possible conditions under which various contractors operate; the difference in type of equipment; potential lost motion, etc., from shutdowns; and other difficulties. In 1981, the TRB Committee on Construction Equipment decided that the fuel factors still represented the overall range of use. However, factors showing gallons of fuel for each $1,000 of construction, based on 1973 and 1974 dollars, are no longer valid because of inflation. Because the fuel use factors (*24*) are generally based on overall fuel purchases by a contractor, they include losses due to spillage, fuel used in transporting personnel, and nonproductive travel by contractor equipment. Consequently, these factors are higher for some indicated operations than corresponding factors calculated from the standpoint of time of operation and the horsepower of specific equipment. The Federal Highway Administration (FHWA) recognizes the factors as useful guidelines in its technical advisory concerning the development and use of price adjustment provisions (*26*). This advisory also includes attachments providing fuel use factors reported independently by states and fuel costs as a percentage of total cost by type of construction. These attachments are reproduced in Tables 11 and 12.

TRANSPORT (HAULING) ENERGY

The estimates in Tables 10 and 11 do not permit specific assessment of the effect of haul distance on the movement of materials, an important consideration for highway projects. A precise measure of the amount of fuel used to move materials is not possible because many variables affect such

TABLE 10
FUEL USE FACTORS FOR HIGHWAY CONSTRUCTION (*24*)

Item of Work	Units	Diesel			Gasoline		
		Low	Avg.	High	Low	Avg.	High
Excavation:	Gallons/Cu.Yd.						
Earth		0.27	0.29	0.30	0.11	0.15	0.21
Rock		0.37	0.39	0.42	0.17	0.18	0.22
Other		0.33	0.35	0.38	0.15	0.16	0.18
Aggregates:	Gallons/Ton						
Onsite Production		0.25	0.28	0.36	0.08	0.09	0.11
Aggregate Base							
0-10 Mi. Haul		0.24	0.27	0.33	0.22	0.24	0.28
10-20 Mi. Haul		0.35	0.42	0.54	0.27	0.39	0.49
Asphalt Concrete:	Gallons/Ton						
Production		1.75	2.43	3.50	0.07	0.14	0.18
Hauling							
0-10 Mi. Haul		0.28	0.33	0.34	0.35	0.43	0.53
10-20 Mi. Haul		0.30	0.49	0.56	0.35	0.58	0.89
Placement		0.06	0.14	0.20	0.08	0.14	0.22
Portland Cement Concrete Pavement:	Gallons/Cu.Yd.						
Production		0.15	0.28	0.45	0.12	0.15	0.21
Hauling		0.33	0.48	0.67		0.52*	
Placement		0.13	0.22	0.31	0.14	0.23	0.38
Structures:	Gallons/$1,000	10	19	25	10	22	35
Miscellaneous:	Gallons/$1,000	10	19	30	10	19	30

*Estimated Figure due to Insufficient Data.

TABLE 11
FUEL USE FACTORS REPORTED BY STATES *(26)*

Items of Work	Units	Diesel	Gasoline	Combined
Clearing and Grubbing	Gal/Acre	-	-	200
Earthwork:				
-Excavation	Gal/C.Y.	-	-	0.25-0.30
-Borrow	Gal/C.Y.	-	-	0.25
-Borrow	Gal/Ton	-	-	0.45
-Loose Riprap	Gal/C.Y.	0.39	0.18	-
-Granular Backfill	Gal/C.Y.	1.00	0.16	-
Aggregates:				
-Base Course	Gal/C.Y.	0.82-0.88	0.55-0.57	1.30
-Base Course	Gal/Ton	0.55-0.63	0.09-0.40	0.65
-Stabilization (mixing)	Gal/S.Y.	0.04-0.044	0.028-0.03	-
-Uncrushed Base	Gal/C.Y.	-	-	0.45
-Uncrushed Base	Gal/Ton	-	-	0.25
Asphalt Concrete:				
-Pavement	Gal/Ton	2.57-2.90*	0.28-0.78	3.50
-Open-Graded	Gal/S.Y.	0.07	0.02	-
-Pavement Widening	Gal/S.Y.	0.86	0.24	-
*If natural gas is used for aggregate drying, deduct 2.00 gal/ton.				
Portland Cement Concrete Pavement:				
-Standard	Gal/S.Y.	0.11	0.15	-
-9 inch	Gal/S.Y.	0.245	0.038	-
-10 inch	Gal/S.Y.	0.272	0.042	-
-Shoulders	Gal/S.Y.	0.204	0.031	-
Miscellaneous:				
-Guard Rail	Gal/L.F.	-	-	0.23
-Concrete Barrier	Gal/L.F.	0.20	0.10	
-Lighting and Signing	Gal/$1000 1/	-	-	15.0
-Fencing	Gal/$1000 1/	-	-	53.0

1/ Dollar costs are based on estimates reported to FHWA late 1979 or early 1980.

TABLE 12
FUEL COSTS AS A PERCENTAGE OF TOTAL COST BY TYPE OF CONSTRUCTION *(26)*

Type of Construction	Fuel Cost Percentage
Grade and drain	13-15
Grade, drain, and structures	9-10
Grade, drain, and pave	10-13
Grade, drain, pave, and structures	9-11
Surface and resurface - bituminous	9-15
Bituminous patching	11
Base and subbase	10
Portland cement concrete pavement - rural	5
Portland cement concrete pavement - urban	10
Concrete pavement patching	9
Structures and approaches - rural	5-6
Structures and approaches - urban	3-6
Deck repair, or minor widening	2
Electrical work	2
Landscaping	5
Pavement marking	1

movements. The type of equipment used, the load factor for each movement, speed, terrain, traffic conditions, and even driving habits of the operator can all affect fuel use. Nevertheless, general estimates based on gross movements by types of equipment and average miles per gallon for such equipment have been made and provide useful guidelines.

In calculating energy requirements for various types of trucks hauling highway materials, the Asphalt Institute considered asphalt tank trucks as four- and five-axle rigs and dump trucks were considered three-axle rigs *(4)*. These data are based on 1970 truck operations, and the data have not been updated.

The improvements in truck efficiency over the recent few years are most effective for large vehicles hauling essentially maximum capacity loads at legal speeds over Interstate-quality highways. The conditions conducive to better efficiency generally do not exist for highway construction projects. Much of the material movement may be over unpaved construction roads at low speeds and at inefficient gear ratios. Exceptions would be long hauls for asphalt cements, portland cements, or aggregates from distant sources to job sites. These would likely be at optimum capacity loads and maximum legal speeds. However, return travel

TABLE 13
ENERGY REQUIREMENTS OF VARIOUS TYPES OF TRUCKS FOR HAULING HIGHWAY CONSTRUCTION AND MAINTENANCE MATERIALS[a]

Truck Type (for hire)	Gasoline Powered (ton-mi/gal)	(Btu/ton-mi)	Diesel Powered (ton-mi/gal)	(Btu/ton-mi)
2 axle, 6 tires	11.34	11,000	-	-
3 axle	29.29	4,270	36.56	3,800
3 axle (comb.)	16.81	7,440	23.79	5,840
4 axle (comb.)	24.80	5,040	42.51	3,270
5 axle (comb.)	43.07	2,900	70.75	1,960

[a] Based on data from the Asphalt Institute (4).

in most cases would be empty, thereby reducing overall efficiency on the basis of tonnage hauled (*27*).

Data from a test with truckers driving tractor trailers of different weights and hauling different payloads showed that in essentially all cases fuel use at 55 mph was less than at higher speeds (*27*). The average of all trucks in the test at 55 mph was 5.52 mpg, with a range of 4.39 to 7.4 mpg. Computations made for optimum gear ratios for these trucks showed that the average could be increased to 5.86 mpg with a range of 5.01 to 7.40 mpg.

Conversation with a representative of the American Trucking Associations indicated that tractor-trailer combinations operating at maximum axle loads would carry about 20 to 25 tons, and get between 5.2 to 5.6 mpg under optimum conditions. On the basis of 22 tons loaded and one-way empty travel, the average payload for such trucks would be 11 tons, and assuming an average of 5.2 mpg, this type of truck uses 2,430 Btu/ton-mi.

The value of 2,430 Btu/ton-mi is intermediate between that reported for three-axle and five-axle rigs by the Asphalt Institute (Table 13). Asphalt cement, aggregates (long haul), and portland cements would likely be moved in this type of vehicle. This value is also close to the value of 2,343 Btu/ton-mi estimated for all highway freight movements by the U.S. Department of Transportation (*28*). Estimates by Cope in 1974 indicated fuel use for the trucks in his test of 4.81 mpg (*29*). Gasoline-fueled dump trucks (hauling capacity of 4 yd^3) used by the Virginia Department of Highways were reported to average 5.17 mpg (*30*). Similar trucks with diesel engines were estimated to get 8.35 mpg.

Maintenance trucks with diesel engines have been reported to use 26,700 Btu/mi (*12*). Because the average loading for such trucks cannot be determined, and because most published data report 5 mpg as the rate of fuel consumption, perhaps three-axle gasoline dump trucks can be assumed to use 5 mpg under conditions used for highway construction. Similarly, diesel-operated trucks could be assumed to use 7 mpg for highway construction. At 5 mpg, gasoline-operated trucks would use 0.20 gal/mi or about 25,000 Btu/mi. At 7 mpg, diesel trucks would use 0.143 gal/mi or about 20,000 Btu/mi.

For long highway hauls using maximum wheel loads, most vehicles are diesels and 5 mpg appears to be a reasonable average rate of fuel consumption. This converts to 27,800 Btu/mi.

To make estimates based on gallons of fuel per ton-mile, estimates of the average expected loads for the conditions of the project in question could be made. However, in the absence of such data, the estimates in Table 14 provide a reasonable basis for comparison. The values in Table 14 indicate a lower efficiency, on the basis of gallons of fuel per ton-mile, than those in Table 13.

CONSTRUCTION ENERGY

Energy used by construction equipment and fixed-plant operations vary significantly with the conditions at the construction site and the manner of use—amount of idling, lost motion, for example. The design and operation of plants (such as for aggregate processing and asphalt mixing) also affect energy use.

The estimated total fuel use factors for highway construction work, including excavation, production of aggregates

TABLE 14
ESTIMATES OF FUEL USE BY TRUCKS HAULING HIGHWAY CONSTRUCTION MATERIALS

Material Hauled	Type of Equipment	Average Fuel Economy (mpg)	Assumed Full Load (tons)	Fuel Use[a] (gal/ton-mi)	(Btu/ton-mi)
Aggregate, sand, asphalt cement, portland cement	Diesel 5 axle	5	22	0.0182	2,500
Asphalt hot mix, recycled material, portland cement concrete	Diesel 3 axle	7	10	0.0286	4,000
	Gasoline 3 axle	5	10	0.0400	5,560

[a] Vehicles are assumed to move one way fully loaded and return empty. Distance traveled is twice the distance between the point of origin and the point of delivery. If vehicles are loaded both ways, fuel use would be approximately one-half of the values given.

TABLE 15

ESTIMATED TOTAL FUEL USE FACTORS FOR HIGHWAY CONSTRUCTION ACTIVITIES[a,b]

Item of Work	Unit	Equivalent Gallons of Diesel Fuel Low	Average	High
Excavation				
Earth	ton	0.37	0.42	0.49
Rock	ton	0.52	0.55	0.62
Other	ton	0.46	0.49	0.54
Aggregates				
Production	ton	0.32	0.36	0.46
0-10 mi haul[c]	ton	0.44	0.49	0.58
11-20 mi haul[c]	ton	0.59	0.77	0.98
Asphalt Concrete				
Production	ton	1.81	2.56	3.66
0-10 mi haul	ton	0.28	0.33	0.34
11-20 mi haul	ton	0.30	0.49	0.56
Placement	ton	0.06	0.14	0.20
Portland Cement Concrete[d]				
Production	yd^3	0.26	0.41	0.64
Hauling	yd^3	0.33	0.48	0.67
Placement	yd^3	0.13	0.22	0.31

[a] Based on data from Circular No. 158 (24).

[b] This table gives the data from Table 10 in terms of equivalent gallons of diesel fuel. Where appropriate, the gasoline volumes in Table 10 were converted to equivalent gallons of diesel fuel and combined with the diesel fuel factors.

[c] Includes hauling, spreading, compacting, and finishing of base.

[d] A cubic yard of concrete is assumed to weigh 2 tons.

and asphalt concrete, and others, are given in Table 15. Other construction energy factors, including loading, heating, and drying aggregate, etc., are given in Appendix B.

Operation of Asphalt Concrete Plants

Estimates of fuel use in preparing asphalt concrete mixtures are available in published literature (*4, 11, 31, 32*). An update on fuel conservation issued by the National Asphalt Pavement Association (NAPA) provides realistic data obtained after the 1973-74 oil embargo (*31*). Fuel and energy factors have been studied for aggregate drying based on theoretical considerations (*32*). Improved practices and conservation efforts between 1970 and 1977 have been shown to reduce the average consumption of No. 2 fuel oil in asphalt paving from 4.26 to 3.25 gal/ton of asphalt concrete placed (*31*). An average of 3.0 gal/ton of asphalt concrete was estimated to be achievable through industry-wide efforts (2.0 gal/ton for heating and drying aggregates and 1 gal/ton for hauling, placing, and rolling).

Conservation efforts should concentrate on the use of fuel for drying (*31*). Protection of aggregate stockpiles to reduce moisture in the pile is shown to be the most effective measure for this reduction. As a rule of thumb, 1 percent reduction in aggregate moisture content produces a 10 percent reduction in fuel requirements (Table 16). Careful control of the volume of intake air and of the temperature of the exchange yields significant fuel savings (*31*).

Based on previous data that about 26,000 Btu is needed to heat and dry 1 ton of aggregate with a 5 percent moisture content, the Asphalt Institute estimated that 28,000 Btu (0.20 gal diesel fuel) is used to remove 1 percent moisture from 1 ton of aggregate and 470 Btu is needed to heat 1 ton of aggregate 1°F (*4*). The energy used to remove the moisture (28,000 Btu × 5) was subtracted from the total and the difference was divided by 255, the number of degrees by which the temperature was increased (70°F to 325°F) (*4*). Energy use calculated by this formula is about 10 percent lower than that given in Table 16. However, values in Table 16 are more closely related to present-day practice because they were derived from a more thorough study conducted after publication of the Asphalt Institute report (*4*).

Because other conventional plant operations take place under a wide range of conditions, all estimates on energy use for asphalt concrete production are based on assumptions that could differ considerably from actual conditions. Estimates of the energy used for a dryer-drum asphalt mixing plant assume that the energy consumed during asphalt storage and cold feed and for the dryer and exhaust (blowers, etc.) (Table 17) is the same as the amount of energy used by the conventional plant. However, the energy used for the asphalt pump and storage conveyer is estimated at 650 Btu/ton giving a total of about 16,000 Btu/ton for dryer-drum plants.

TABLE 16

FUEL REQUIRED TO DRY AGGREGATE (ASPHALT PLANTS)[a]

Moisture Content[b] of Aggregate (%)	No. 2 Fuel Oil[c,d] per Ton of Aggregate (gal)
10	3.04
9	2.82
8	2.61
7	2.40
6	2.19
5	1.98
4	1.76
3	1.55
2	1.34

[a] Based on data from NAPA (31).

[b] Based on dry weight of aggregate.

[c] Entrance conditions:

Aggregate, fuel, and air	70°F
Moisture content of aggregate	As shown
Air volume	R = 2

[d] Exit conditions:

Aggregate	325°F
Moisture content of aggregate	0%
Dryer exhaust	350°F
Plant elevation	636 ft

TABLE 17
ESTIMATED ENERGY USE IN CONVENTIONAL ASPHALT PLANT OPERATIONS[a]

Item	Hot-Mixed Asphalt Concrete (Btu/ton)
Asphalt Storage[b]	6,400
Cold Feed[c]	4,730
Dryer and Exhaust Fans, etc.[d]	4,770
Mixing Plant[e]	3,920
Total	19,820
	(Round to 19,800)

[a] Based on data from the Asphalt Institute (4).

[b] Based on average plant use.

[c] Based on gasoline use of 7 gal/hr with production of 200 ton/hr plus 0.07 hp-hr/ton calculated at 0.06 gal/hp-hr and two-thirds operational efficiency.

[d] Based on 0.95 hp-hr/ton at two-thirds operational efficiency and 0.06 gal/hp-hr.

[e] Based on 0.78 hp-hr/ton at two-thirds operational efficiency and 0.06 gal/hp-hr.

Operation of Plants Producing Portland Cement Concrete

The operation of a loader for aggregate at a portland cement concrete mixing plant is estimated to use 4,375 Btu/ton of aggregate and the energy used in the operation of the conveyer is estimated as 265 Btu/ton—yielding a total of 4,640 Btu/ton of aggregate handled (*4*). The operation of a batching plant uses about 3,565 Btu/yd^3 of concrete. On the basis of about 2 tons of aggregate for 1 yd^3 of concrete, the energy needed to mix 1 yd^3 of concrete is about 12,800 Btu. This value is about one-third of a reported low use value for producing portland cement concrete and only about one-seventh of a high use value (*24*). It is likely that these published values (*24*) include waste fuel and unproductive operations; nevertheless, no explanation for such large discrepancies could be found.

Placement and Compaction of Asphalt Pavements

About 0.12 gal of diesel fuel/ton (16,700 Btu/ton) is estimated for placement and compaction, assuming a 150 ton/hr production with a paver and 3 rollers, each using 4.5 gal of diesel fuel/hr (*4*). This value is close to the average of 0.14 gal/ton given in Table 15; it represents a relatively small proportion of the total fuel required.

Placing and Finishing Portland Cement Concrete Pavements

A production rate for portland cement concrete pavement of 300 yd^3/hr is assumed with a placer-spreader and paver (*4*). Each piece of equipment is diesel-operated at 175 hp at 75 percent of rated capacity (*4*). Thus, 2 units at 175 hp × 0.75 efficiency × 0.04 gal/hp-hr × 139,000 Btu/gal gives about 1.46×10^6 Btu/hr.

The two gasoline units for finishing and curing (10 hp each) consume 112,500 Btu/hr (2 × 10 × 0.75 × 0.06 × 125,000). The total is 1.572×10^6 Btu/hr. This is equivalent to 5,240 Btu/yd^3 of concrete, which is equivalent to 0.038 gal of diesel fuel. This value is only about one-sixth of the average reported for portland cement concrete pavement in Table 15.

An independent survey made by the National Ready-Mix Concrete Association (NRMCA) showed that on the basis of reports from 41 of its members in 1975, fuel use averaged 1.0 gal/yd^3 of production delivered (R. Gaynor, Director, NRMCA; *personal communication*). This included both diesel- and gasoline-operated trucks with the ratio of gasoline to diesel being about 2:1. The standard deviation of these data was 0.49 gal. Eighteen companies reported fuel use of between 0.5 and 0.99 gal/yd^3 and nine companies reported fuel use between 1.00 and 1.49 gal/yd^3.

These values reported by the NRMCA are generally of the same order of magnitude as the total fuel use reported in Table 15 for the production and placement of portland cement concrete. No basis for judging the accuracy of the various estimates is available. However, estimates by the Asphalt Institute (*4*) are based on somewhat idealized conditions and include estimates only for the basic equipment being used. Other estimates, such as those in Table 15, and those by NRMCA, most likely include fuel for support equipment, pickup trucks, automobiles for personnel movements, etc., as well as any evaporation or spillage losses, and are probably more realistic from a practical standpoint than the estimates reported by the Asphalt Institute (*4*).

The energy required to saw the joints in portland cement concrete pavement is estimated as 280 Btu/linear ft (*4*).

MAINTENANCE OPERATIONS

Energy requirements for activities for miscellaneous maintenance and rehabilitation equipment used to rehabilitate pavement are summarized in Table 18 (*33*).

TABLE 18
REPRESENTATIVE ENERGY REQUIREMENTS FOR HIGHWAY MAINTENANCE AND REHABILITATION ACTIVITIES (*33*)[a]

Maintenance Activity	Energy Requirements					Percent of total Pavement area treated & other Assumptions
	Energy/unit	Btu/yd^2 of area treated	Btu/yd^2 in.	Btu/lane mi*	Btu/yd^2*	
Fog Seal-Partial Width	10,500 Btu/gal	1,050		3,700,000	525	50 percent
Fog Seal - Full Width	6,850,000 Btu/lane mi 3,300,000 Btu/lane mi[b]	970 470[b]	-	6,850,000 3,300,000[b]	970 470[b]	100 percent
Chip Seal - Partial Width	537,000 Btu/yd^3	4,480	-	4,700,000	670	15 percent
Chip Seal - Full Width	14,400,000 Btu/lane mi 27,800,000 Btu/lane mi[b]	2,050 3,950[b]	-	14,400,000 27,800,000[b]	2,050 3,950[b]	100 percent
Surface Patch - Hand Method	Data Not Available					2.5 percent 1 in. thick
Surface Patch - Machine Method	1,070,000 Btu/yd^3	29,800	29,800	21,000,000	2,990	10 percent 1 in. thick
Digout & Repair Hand Method	1,600,000 Btu/yd^3	178,000	44,460	25,000,000	3,560	2 percent 4 in. thick
Digout & Repair Machine Method	1,120,000 Btu/yd^3	187,000	31,200	65,800,000	9,350	5 percent 6 in. thick
Crack Pouring	32,400 Btu/lane mi[c] 33,500 Btu/gal[d]		- -	8,500,000 3,900,000	1,220 560[d]	250 lin. ft per station
Slurry Seal	9,400,000 Btu/lane mi	1,340[c]	-	9,400,000	1,340[c]	100 percent
Asphalt Concrete Overlay	512,000 Btu/ton[b] 533,000 Btu/ton[e]	55,600[b] 57,800[e]	27,800[b] 28,900[e]	391,000,000[b] 407,000,000[e]	55,600[b] 57,800[e]	100 percent 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.

[a] Ledbetter (33) reported that all data in this table were based on personal communication with W. G. Fleischli, D. R. Posell, and S. F. Lanford, Arizona Department of Transportation, except for the items noted below.

[b] Data from the Asphalt Inatitute (4).

[c] Data from Slurry Seal, Inc. (34).

[d] Personal communication with R. Neal, Texas State Department of Highways and Public Transportation.

[e] Data from Circular No. 158 (24).

CHAPTER FIVE

ENERGY CONSERVATION IN HIGHWAY CONSTRUCTION AND MAINTENANCE

A major consideration in highway construction and maintenance operations is reduction of costs through energy conservation. This includes the conservation of materials and energy through a variety of methods and technologies as well as the utilization of wastes, by-products, and salvaged materials.

USE OF LOCAL MATERIALS AND MODIFICATIONS OF CONSTRUCTION METHODS

Conservation of energy in the base courses and embankments can be achieved by the use of on-site materials, which minimizes the expenditure of transport energy. The costs and energy requirements for stabilization procedures must be compared with costs and energy requirements for removing and replacing unsuitable materials. Another significant factor in earthwork construction, such as embankments, is the optimum utilization of equipment that can place and compact material in thicker than usual lifts. However, in some cases, state specifications continue to require limited thicknesses with the expenditure of appreciably more energy.

In 1975 a recommendation was made that the requirements to remove stumps and topsoil from areas to be filled be reconsidered (*35*). A number of states now permit such materials to be left in place where grade lines are more than 6 ft above the existing surface.

Suggestions have also been made that changes be permitted in geometric designs to allow steeper side slopes and altered grade and sight distances to reduce earthwork volumes. However, such actions could adversely affect safety and might also lead to overall expenditures of greater amounts of energy, because vehicles using the finished roadway would consume larger amounts of energy in travel. In most cases, the energy in the additional fuel used by each of the thousands of vehicles using the pavement with steeper grades would quickly exceed the extra energy needed for constructing flatter grades.

STABILIZATION

For equal volumes of materials moved equal distances, obviously less energy is required for graded aggregate bases than for those stabilized with either asphalt or portland cement, because of the big difference in the processing energy of the materials. However, because different thicknesses are required for equal performance, different volumes of material must be moved. Consequently, stabilization may prove to be the most energy-conservative approach in the long term. The validity of this premise depends to a great extent on the distances involved and the layer equivalency factors used. Alternative types of base courses and their roles in the overall structural adequacy of the pavement have been studied extensively. The debate concerning equivalencies of various types of base courses under different conditions is considered beyond the scope of this report. However, in any consideration of relative energy use for various types of base course construction, it must be recognized that adequate performance of the base is the primary concern in selecting a design.

A base that does not perform as expected can generate dollar and energy costs well beyond the cost of the energy initially saved. Cost-effectiveness and availability of materials are major elements in the selection of the type of base to be used. A recognition of the relative energy impacts can also serve as a useful guide to further research and as an indicator of possible changes in costs or availability of the alternative materials. It is not possible to indicate the relative amounts of energy consumed for different types of bases for all situations. Because of differences in hauling distances, each project must be analyzed separately. However, estimates of energy required for various steps in the process can be made for use in such analyses.

ASPHALT CONSTRUCTION

Two significant opportunities for energy conservation in asphalt construction are (a) the substitution of asphalt emulsions for asphalt cutbacks and (b) the reduction of asphalt mixing temperatures. Halstead (*36*) estimates that the 4.1×10^6 tons of asphalt cutback used in 1975 contained 345×10^6 gal of petroleum distillates. An estimated 263×10^6 tons of asphalt cutback were sold in 1979 (*37*). Thus, the equivalent of about 200×10^6 gal of diesel fuel are still being used in cutbacks and a significant potential for further reduction exists.

A potential exists for saving diesel fuel by production of asphalt mixtures at lower temperatures (*38*). Drum mixers operated at temperatures at which a considerable amount of initial moisture in the aggregate is not removed offer a potential saving of about 1 gal diesel fuel/ton of mixture. However, problems sometimes occur when moisture is left in the mixture. Consequently, whether energy saving from this alternative of using lower operating temperatures for drum mixers is feasible depends on the circumstances for each project.

HYDRAULIC CONCRETE CONSTRUCTION

The most significant opportunity to conserve energy in hydraulic concrete construction involves the use of fly ash. Fly ash can be incorporated in the blended cement resulting in significant reduction in the amount of processing energy for a unit of hydraulic cement (blended cement compared to regular portland cement). Fly ash can also be used as an ingredient of the concrete at the mixer with an accompanying reduction in the amount of portland cement required. The amount of energy saved in each case is directly related to the reduction in processing energy for the manufacture of portland cement. About 7 × 10^6 Btu is saved for each ton of portland cement clinker not required in the concrete because of the use of fly ash.

UTILIZATION OF WASTES, BY-PRODUCTS, AND SALVAGED MATERIALS

The use of wastes and by-products is often promoted as a means of conserving energy. However, the relative distance of the waste or by-product from the point of its use compared with the distance that conventional materials must be moved has been found to determine the possibility of a significant saving in total energy (*39*). For highway construction, the fuel used in hauling and construction can outweigh any advantage from conservation of processing and calorific energy. Although such savings in total energy may be significant from the standpoint of the overall national picture, no direct advantage in highway construction can be realized unless material or construction costs are reduced.

However, there are other reasons for using waste and by-products, the most important being (a) opportunities to conserve the supply of high-quality materials when the waste or by-product can perform adequately and (b) reduction or elimination of potential damage to the environment from storage of waste products. In a study of the potential for utilization of wastes and by-products in Virginia, the use of fly ash and greater efforts to reuse materials salvaged from old pavements were concluded to offer the best opportunities for waste utilization in that state (*39*). These findings are generally applicable for most of the United States, except in some areas where mining wastes and slags may be available.

Reusing materials salvaged from both asphalt and portland cement concrete pavements is generally recognized as offering an excellent potential for conserving energy and materials and for reducing costs. Accordingly, considerable efforts are now being made to develop the needed technology. The published proceedings of a 1980 national seminar on asphalt pavement recycling summarized the state of the art in this area (*40*). A conference on the rehabilitation of portland cement concrete in September 1981 similarly summarized the present state of knowledge and technology for this highway construction material (*41*).

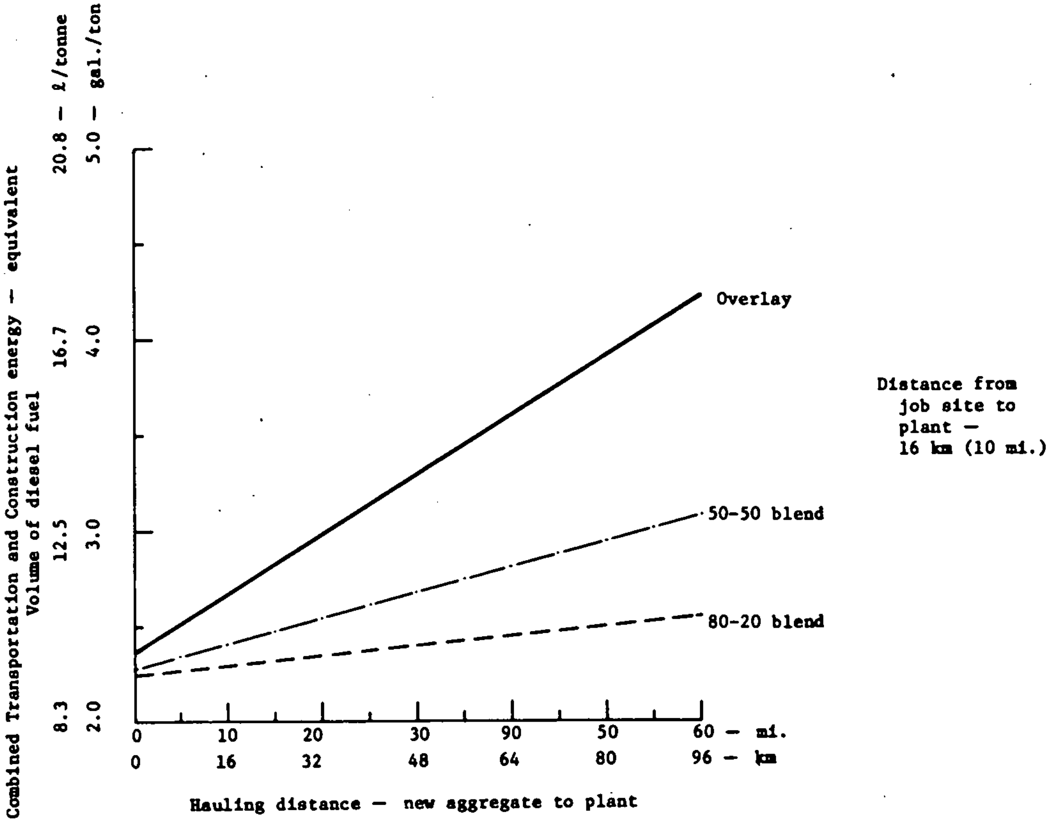


FIGURE 4 Effect of the distance that new aggregate must be hauled to plant on energy consumption in central-plant recycling (*42*). Blend ratios indicate relative proportion of reclaimed mixture to new aggregate.

Recycling of Asphalt Pavements

In asphalt recycling, the relative amounts of energy consumed in hauling and construction for alternative procedures were found to be the major concern in highway construction and maintenance (*42*). The energy consumed in the recycling of asphalt determines, to a considerable extent, the relative costs of different alternatives (*42*). In a summary of the energy savings and cost reductions reported for the recycling projects included in the Federal Highway Administration's Demonstration Project 39, only two of the 21 projects reported negligible savings in energy. The reported figures for energy conservation ranged from a low of 390 to a high of 7,730 gal of diesel fuel saved for 1 lane-mi of recycled pavement. Because a wide variety of recycling techniques was used in these projects and comparisons were made with different rehabilitation procedures, a wide range in energy savings was not unexpected. The important point is that, in the projects constructed, recycling proved to be less costly and used less energy than conventional methods (*42*). Whether all measures are cost-effective or energy-conservative in the long term remains to be determined.

The effects of haul distances on the potential for conserving energy have been analyzed (*42*). Significant and rising initial savings of energy are possible by recycling when new aggregate must be hauled to the asphalt plant over increasingly longer distances (Figure 4). This energy conservation advantage of recycling can be lost when the material to be recycled must be hauled significantly farther than new aggregate (Figure 5).

Halstead's analysis of asphalt recycling costs and energy conservation features did not consider potential savings in processing energy from the reuse of the aggregate and the asphalt in the salvaged material (*42*). For each ton of salvaged material used, essentially 1 ton less of new aggregate must be processed and only about 2 percent of additional asphalt is required instead of about 5 percent for all new materials. Thus, the reduction in needed processing energy is 58,100 Btu for the aggregate and 20,500 Btu for asphalt (0.035 × 587,000) for each ton of salvaged material. This is equivalent to about 0.6 gal of diesel fuel/ton of salvaged material used. The reduction in calorific energy requirements, because less asphalt is used, is equivalent to 1.3×10^6 Btu, or 9.35 gal of diesel fuel/ton of salvaged material used.

Recycling of Portland Cement Concrete Pavement

Portland cement concrete pavement can be recycled in a number of ways (*12, 43*), including: (a) as graded aggregate base, (b) as cement-treated base, (c) as asphalt base course and pavement, (d) as portland cement concrete base and pavement, and (e) as a source of aggregate in miscellaneous construction, e.g., backfill.

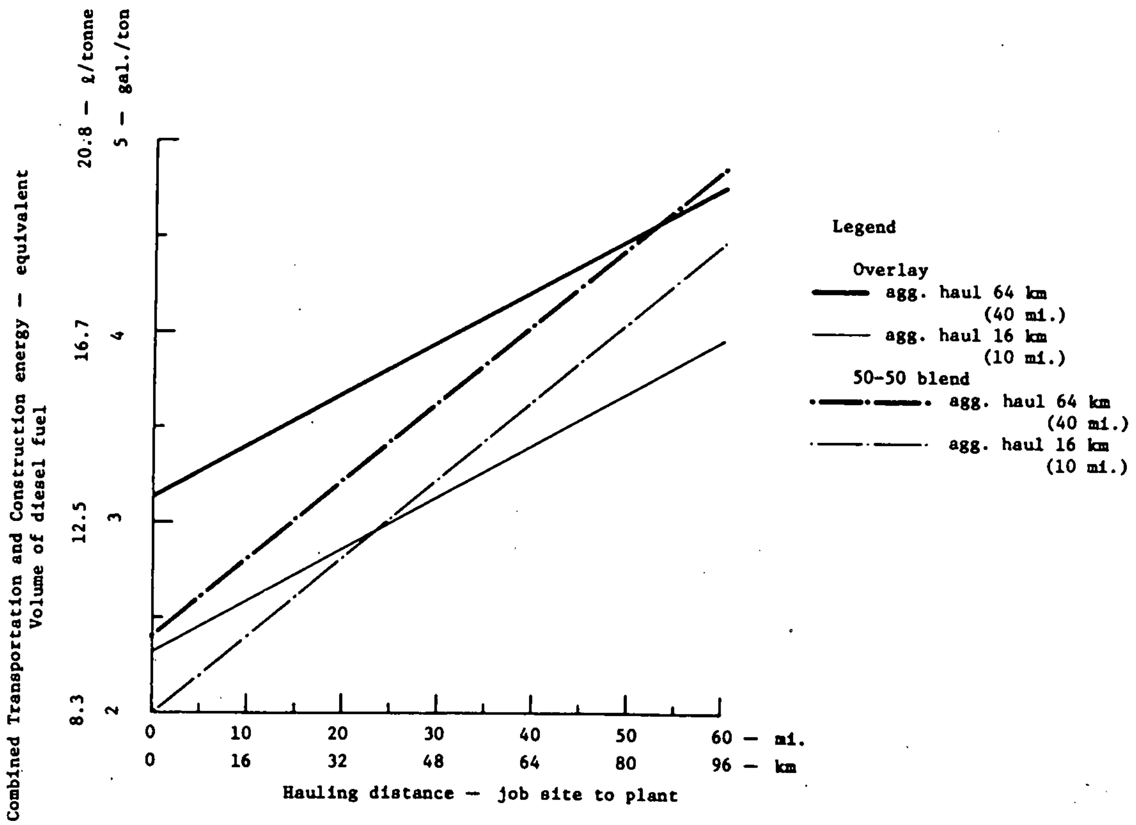


FIGURE 5 Effect of hauling distances from job site to plant on energy consumption in central-plant recycling (*42*).

In all of these applications the most significant energy saving results from a reduction of hauling energy. The greatest saving occurs when the old pavement can be crushed and reused in lieu of new aggregate at the same site. Under these conditions substantial savings can be realized from not having to remove the materials to a disposal site as well as not having to bring in new material. The saving in processing energy when using salvaged portland cement concrete pavements in lieu of new aggregate is the difference between that required for crushing the new aggregate and that required for crushing the old pavement. In many instances the energy required for these two crushing operations will be equivalent. The presence of reinforcing steel in the old pavement could strongly affect the energy consumption.

Field experience, specifications, mixture design, quality control, and environmental concerns for recycling portland cement concrete are described in the literature (*41*).

CHAPTER SIX

ESTIMATES OF ENERGY REQUIREMENTS FOR HIGHWAY CONSTRUCTION USING DIFFERENT MATERIALS AND PROCEDURES

Available data represent only general estimates of energy use for various highway purposes. However, this information can be useful in providing a perspective of the overall relationships between categories of energy and how future changes in cost and energy supply may affect highway construction.

Computations of energy requirements for several types of base courses and surfaces are presented in Appendix B for (a) construction energy, (b) transport energy, (c) processing energy, and (d) calorific energy. The energy requirements so calculated are based on assumptions of typical, or in some cases extreme, conditions and may not be applicable to all projects.

Appendix B also includes the details of the computations, the factors used, and the source of those factors. When more precise information on the distances involved and the design of the pavement components for a project are known, computations should be based on such known factors. The step-by-step computations provided in Appendix B can serve as a guide for such computations.

ENERGY REQUIREMENTS FOR BASE COURSES

Estimates of the amounts of energy required for each inch of thickness for the construction of various types of base courses and for both short-haul and long-haul situations are presented in Table 19. The separate estimate for energy required in each category provides insight into differences in the manner energy is required as well as the total amounts involved. The sum of the construction energy (E_c) and the transport energy (E_t) approximates the amount of direct fuel energy that the highway contractor must purchase.

The significance of transport energy for crushed stone base is clearly illustrated by the data in Table 19. If the hauling distance is 20 mi (short haul), the transport energy constitutes 60 percent of the total energy required. At 130 mi (long haul) the transport energy constitutes 89 percent of the total energy. The potential for saving direct fuel energy by using emulsions to upgrade local material can be judged by comparing the construction plus transport energy required for different hauling situations.

Assuming that the mixing plant would operate at the source of the local aggregate and an average 10-mi haul (short haul) is required for the mix and that the alternative is to bring in crushed stone from a 130-mi distance (long haul), the emulsion-treated base would require 700 gal/in. of thickness as compared to 3,700 gal for crushed stone—a ratio of 5 to 1 in favor of the emulsion treatment. However, the ratio changes significantly when calorific and processing energies are included. In this case, on an inch-for-inch basis, the total energy for crushed aggregate is estimated to be only about one third of that for the emulsion-treated base.

A greater amount of energy is required for hot-mix asphalt concrete (HMAC) than for crushed stone at equal thicknesses and equal long-haul distances (Table 19). However, if 1 in. of HMAC is considered to be equivalent to 3 in. of crushed stone and the stone must be hauled a long distance (130 mi, in the example), the direct fuel energy required for HMAC is only about one third that for the crushed stone. Again, however, when calorific energy of the asphalt is included, the total energy requirement for HMAC is about equal to that for the crushed stone base even on a 3:1 basis and long haul.

The direct fuel energy (E_c plus E_t) required for lean concrete bases compares well with that required for crushed stone or emulsion-treated base. However, the processing energy for the cement significantly increases the total for all categories. The advantage of not having to haul the aggregate long distances is illustrated by the low estimated total of construction and transport energy for road-mixed, cement-treated subgrade.

These comparisons demonstrate that the relative requirements for energy by different types of materials and construction processes depend to a considerable extent on the hauling distances involved for a given project. Estimates of

TABLE 19
ENERGY USED TO CONSTRUCT VARIOUS TYPES OF HIGHWAY BASE COURSES (gal/mi-in.)[a]

Type of Base	Construction E_c	Transport Short E_t	Transport Long E_t	Processing E_p	Calorific E_h	Total[b] $E_c + E_t$	Total[b] All Categories
Crushed Stone	115	545	3,540	299	0	Short 700 Long 3,700	1,000 4,000
Emulsion-treated local aggregate	126	531	1,376	1,116	11,412	Short 700 Long 1,500	13,200 14,000
Hot-mixed asphalt concrete	1,649	781	4,173	452	9,200	Short 2,400 Long 4,000	12,100 15,500
Lean concrete; local or recycled aggregate	246	570	2,410	2,622	0	Short 800 Long 2,700	3,400 5,300
Road-mixed, cement-treated subgrade	182	86	86	2,445	0	300	2,700

[a] Expressed as equivalent gallons of diesel fuel per mile of pavement for each inch of thickness. See Appendix B for assumptions made and details of computations.

[b] Rounded to the nearest 100 gal/mi-in.

relative energy requirements must also include consideration of layer equivalences for equal design as well as the categories of energy to be included in the estimates.

ENERGY REQUIREMENTS FOR SURFACE COURSES

Computations for surface courses (Table 20) reveal significant differences in the energy involved in the different categories for asphalt concrete and portland cement concrete. The construction energy per inch of thickness for asphalt concrete is much greater than that for portland cement concrete. Transport energy is not significantly different on the basis of the same assumptions of hauling distances, but the effect of the distance is illustrated by the large difference between the short- and long-haul estimates.

Processing energy (excluding calorific energy) for asphalt concrete is much lower than that for either plain or reinforced concrete. However, when the calorific energy of the asphalt is included, the total energy requirement for asphalt concrete exceeds that for portland cement concrete.

TABLE 20
ENERGY USED TO CONSTRUCT VARIOUS TYPES OF HIGHWAY PAVEMENT SURFACES (gal/mi-in.)[a]

Type of Surface	Construction E_c	Transport Short E_t	Transport Long E_t	Processing E_p	Calorific E_h	Total[b] $E_c + E_t$	Total[b] All Categories
Asphalt concrete (HMAC)	1,605	676	4,602	388	10,220	Short 2,300 Long 6,200	12,900 16,800
Portland cement concrete (no steel)	246	760	4,236	5,912	0	Short 1,000 Long 4,500	6,900 10,400
Reinforced portland cement concrete	246	775	4,251	7,289	0	Short 1,000 Long 4,500	8,300 11,800

[a] Expressed as equivalent gallons of diesel fuel per mile of pavement for each inch of thickness. See Appendix B for assumptions made and details of computations.

[b] Rounded to the nearest 100 gal/mi-in.

CHAPTER SEVEN

LIMITATIONS OF PRESENT DATA AND FURTHER NEEDS

Essentially all presently available data concerning energy factors for highway construction and maintenance materials are estimates based on averages. Energy requirements for highway construction operations are based either on gross fuel energy needs for overall volume of production or on assumptions of average efficiencies of motors and typical operating conditions. Such estimates, when used properly, provide good insights into overall energy requirements for highway construction and maintenance and indicate those areas for which conservation measures would likely be most effective. Good indications can also be attained for the relative energy requirements of alternative processes using similar materials. However, the use of total energy estimates as a major consideration for selecting alternative materials for construction of highways is questionable. In any such selection the technological considerations and the availability and costs of materials should be given primary consideration.

It has been said that all British thermal units are not created equal. It can also be said that all British thermal units are not interchangeable. Thus, in any evaluation of the energy impact of highway construction and maintenance operations, the basic source of the processing energy, for example, whether based on coal, gas, or petroleum, is an important consideration. Similarly, the importance of calorific energy in the material itself varies with the economic value of the material used as a fuel.

The relative significance of processing, construction, transport, and calorific energy differs for the various materials and processes used in highway construction. The highway contractor will be concerned primarily with the amount of fuel that must be purchased to operate equipment and to move materials. Although processing and calorific energy will have a significant role in the cost and availability of different materials, the contractor has no control over the amount of energy used to produce these construction materials. Cost effectiveness remains the overriding consideration for highway construction.

Improved estimates of energy use for specific materials and processing activities and fuel used by specific construction operations are desirable. Individual contractors or corporations must decide if the additional time and expense required to maintain such records are worthwhile.

Little information could be found concerning energy requirements for structures such as highway bridges, ramps, etc. Although the energies for processing and hauling each unit of material would be the same as estimated here, the estimates for the totals involved for specific types of structures could not be located in the published literature. The only information found was based on gross estimates for a given dollar amount of construction. These become obsolete with inflation unless the year the dollar costs were estimated is recorded and, even when such information is available, adjustment on the basis of the overall inflation index is not realistic.

Actual cost increases depend heavily on the energy relationships involved. In his study of indirect energy consumption for transportation projects, Smylie gave a range from 12.0×10^6 kWh thermal (kWht) per lane-mile of bridge to 95.9×10^6 kWht, with an average of 38.2×10^6 kWht (*10*). By his definition, a kWht includes the conversion efficiency of the electrical power plant where electrical energy is used. Thus, a kWht is equivalent to 11,000 Btu or 0.079 gal of diesel fuel as defined in this synthesis. The estimates convert to 0.948×10^6 equivalent gal of diesel fuel for the minimum fuel use to 7.58×10^6 equivalent gal for the maximum use. The average was about 3×10^6 gal/lane-mile of bridge. Such data provide no information concerning specific types of bridges.

There may be a need for more precise estimates on the amount of energy used in the construction of both pavements and structures for the following reasons. Under conditions existing in the United States before 1973, the low cost of energy and the relatively high cost of labor made it desirable to accomplish as much of the highway construction work as possible by machine in order to minimize labor costs. However, under present conditions with the cost of energy increasing more rapidly than labor costs, a study to determine whether or not labor could economically replace some machine operations would be valuable. Such a study would take a long-range view of changes and include more precise data on the use of energy in constructing highways, bridges, and related structures. This would require a central data collection agency, using an established format, and the full cooperation of individual highway contractors in keeping detailed records and sharing them with a central agency.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations represent the more significant findings of this synthesis.

1. Essentially all available energy use factors for highway materials and construction processes are estimates based on assumptions of average or typical conditions. Consequently, estimates based on such factors do not represent a precise evaluation of the energy requirements for any given project.
2. Estimates of the energy required to produce or fabricate different materials for highway construction and the energy needed to carry out processes for highway construction and maintenance reveal the relative amounts and types of energy involved in different highway construction materials and processes. However, it is recommended that energy computations include separate determinations of construction, transport, processing, and calorific energy, and that the relative amounts for different processes and materials be given consideration in any decisions concerning alternatives, or in any statements concerning the energy impact of highway construction.
3. Energy cost and availability markedly affect the costs and cost increases of highway construction and maintenance projects. However, safety, an ability to provide high-quality performance, and cost effectiveness should remain the major factors influencing decisions on highway design. Modifications in procedures or changes in materials simply to save energy are not recommended if any of these factors are adversely affected.
4. The factors for various highway operations reported in *Highway Research Circular No. 158* (*24*) constitute the most useful guidelines presently available for actual fuel consumption on highway projects. The average values reported in this publication generally will be higher than comparable values calculated from amounts used in specific steps of calculating energy use, because fuel used in both production and nonproductive activities is included.
5. The fuel required to transport materials varies significantly with the type of trucks used, the loading factors, and manner of operation. The data on average rate of consumption and gallons of diesel fuel per ton-mile given in Table 14 represent a consensus of available information and are useful for estimating the relative amounts of transport energy under different conditions.
6. Use of salvaged materials (recycling) as a means for conserving both energy and materials in highway rehabilitation is a viable alternative to more traditional procedures. The distance that material must be moved is likely to be the determining factor for the cost effectiveness of using salvaged materials.

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APPENDIX A

FACTORS FOR CONVERTING QUANTITIES FROM U.S. CUSTOMARY SYSTEM TO INTERNATIONAL SYSTEM OF UNITS

U.S. Customary	*Metric (S.I)*
1 foot (ft)	= 0.3048 metres (m)
1 yard (yd)	= 0.9144 metres (m)
1 mile (mi)	= 1609 metres (m) = 1.609 kilometres (km)
1 square yard (yd^2)	= 0.8361 square metres (m^2)
1 cubic yard (yd^3)	= 0.7646 cubic metres (m^3)
1 pound (mass) (lb)	= 0.4536 kilograms (kg)
1 ton (short 2,000 lb)	= 907.2 kilograms (kg) = 0.9072 megagrams (Mg)
1 gallon (U. S. Liquid) (gal)	= 3.785 litres (L) = 0.003785 cubic metres (m^3)
1 British thermal unit (International Table) (Btu)	= 1055 joules (J)
1 Btu/lb	= 2326 J/kg
1 Btu/ton	= 1.163 J/kg = 1163 J/Mg
1 Btu/yd^2	= 1262 J/m^2
1 Btu/yd^3	= 1380 J/m^3
1 Btu/yd^2-in.	= 496.9 J/m^2-cm
1 Btu/mile	= 655.7 J/km
1 Btu/ton-mile	= 0.7228 J/kg-km
1 gal/ton	= 4.172 L/Mg
1 gal/yd^3	= 4.951 L/m^3

APPENDIX B

ASSUMPTIONS AND DETAILED COMPUTATION PROCEDURES FOR BASE COURSES AND SURFACES

The computations given here are based on assumptions of conditions and hauling distances often encountered in highway construction. However, the assumed conditions do not always represent actual conditions; therefore, actual energy requirements could vary significantly from these computations.

Table B-1 lists processing and calorific energy factors as equivalent gallons of diesel fuel converted on the basis of 139,000 Btu per gallon (the average factor for calorific energy in diesel fuel).

The details of the computations and the assumptions made for estimating the energy requirements for highway base courses and highway surface courses given in Tables 19 and 20 in Chapter 6 are presented in Tables B-2 and B-3. The source of the Btu factor is identified in each table.

TABLE B-1
PROCESSING AND CALORIFIC ENERGY FACTORS IN TERMS OF EQUIVALENT GALLONS OF DIESEL FUEL[a]

	Conversion Factor	Diesel Fuel Equivalent per gal	Diesel Fuel Equivalent per ton
Processing Energy (E_p)			
Portland Cement	7.232×10^6 Btu/ton		52.03
Asphalt Cement	587,000 Btu/ton		4.22
Crushed Aggregate	58,100 Btu/ton		0.42
Sand, Gravel	15,000 Btu/ton		0.11
Filler	58,100 Btu/ton		0.42
CMS-2 Emulsion	10,200 Btu/gal	0.073	
	241 gal/ton		17.6
MC-70 Cutback	59,500 Btu/gal	0.428	
Reinforcing Steel	24×10^6 Btu/ton		172.7
Calorific Energy (E_h)			
Asphalt Cement	37.1×10^6 Btu/ton		266.9
CMS-2 Emulsion	115,000 Btu/gal	0.827	
MC-70 Cutback	148,000 Btu/gal	1.065	
Portland Cement, Aggregate, Sand, Gravel		None	None

[a] Converted on basis of 139,000 Btu/gal

TABLE B-2
DETAILS OF ASSUMPTIONS AND COMPUTATIONS FOR TABLE 19

1. Crushed Stone Aggregate

Assumptions:

Processing energy = 58,100 Btu/ton (Table 8)
Aggregate is hauled at 0.0182 gal/ton-mi (Table 14)
Aggregate contains 5% moisture when hauled
Energy for loading = 4,400 Btu/ton (4)
Energy for spreading and compacting = 17,000 Btu/ton (4)
Base compacted to 135 lb/ft^3 = 712.8 tons/mi-in. (24-ft width)
Convert Btu to equivalent gallons diesel fuel by dividing by 139,000 Btu/gal

Computations:

Construction energy (loading, spreading, and compacting)
= 4,400 + 17,000 = 21,400 Btu/ton
21,400 x 1.05 x 712.8 ÷ 139,000 = 115 gal/mi-in.

Transport energy
Short haul (20 mi)
= 712.8 tons x 1.05 x 20 x 2 x 0.0182 (Table 14) = 545 gal/mi-in.

Long haul (130 mi)
= 712.8 x 1.05 x 130 x 2 x 0.0182 = 3,540 gal/mi-in.

Processing energy
= 712.8 x 0.42 (Table B-1) = 299 gal/mi-in.

2. Emulsion-Treated Base (Local Aggregates)

Assumptions:

Processing energy (local aggregate) = 15,000 Btu/ton
8% emulsion mixed in plant at local quarry pit
CMS-2 emulsion used
Energy for plant operation = 6,630 Btu/ton (4)
Assume base compacted to 140 lb/ft^3 = 739.2 ton/mi-in. (140 x 5,280 x 24 ÷ 12 ÷ 2000)
Energy for compaction = 17,000 Btu/ton (4)
Emulsion is hauled 50 mi to plant (both short and long haul) (plant at aggregate source)
Mix hauled at 0.0286 gal/ton-mi (Table 14)

Computations:

Construction energy (handling, mixing, compaction)
= 6,630 + 17,000 = 23,630 Btu/ton
= 23,630 x 739.2 ÷ 139,000 = 126 gal/mi-in.

Transport energy
Short haul (10 mi)
For hauling emulsion = 0.08 x 739.2 x 50 x 2 x 0.0182 = 108 gal/mi-in.
For hauling mixture (10 mi) = 739.2 x 10 x 2 x 0.0286 = 423 gal/mi-in.

Long haul (30 mi)
For hauling emulsion (as above) = 108 gal/mi-in.
For hauling mixture (30 mi) = 739.2 x 30 x 2 x 0.0286 = 1,268 gal/mi-in.

Total transport energy
Short haul = 531 gal/mi-in.
Long haul = 1,376 gal/mi-in.

Processing energy
Emulsion
= 0.08 x 739.2 x 17.60 (Table B-1) = 1,041 gal/mi-in.

Aggregate
= (92% of mix) = 0.92 x 739.2 x 0.11 (Table B-1) = 75 gal/mi-in.

Total for mix = 1,116 gal/mi-in.

Calorific energy (CMS-2 emulsion)
0.827 (Table B-1) x 241 x 739.2 x 0.08 = 11,786 gal/mi-in.

TABLE B-2 *continued*

3. Hot-Mixed Asphalt Concrete

Assumptions:

Crushed stone = 58,100 Btu/ton
4.5% asphalt content
Aggregate hauled at 5% moisture
Asphalt hauled 50 mi (both long and short haul)
Energy for heating and drying aggregate = 1.98 gal/ton (Table 16)
Energy for mixing = 19,800 Btu/ton (4)
Energy for spreading and compacting mix = 16,700 Btu/ton (4)
Base compacted to 145 lb/ft^3 = 766 ton/mi-in.

Computations:

Construction energy

Heating and drying aggregate = 766 x 0.955 x 1.98 = 1,448 gal/mi-in.
Mixing = 766 x 19,800 ÷ 139,000 = 109 gal/mi-in.
Spreading and compacting = 766 x 16,700 ÷ 139,000 = 92 gal/mi-in.
Total construction energy = 1,649 gal/mi-in.

Transport energy
Asphalt (short and long haul)
= 766 x 0.045 x 50 x 2 x 0.0182 (Table 14) = 63 gal/mi-in.

Aggregate
Short haul (10 mi) = 766 x 0.955 x 1.05 x 10 x 2 x 0.0182 = 280 gal/mi-in.
Long haul (100 mi) = 766 x 0.955 x 1.05 x 100 x 2 x 0.0182 = 2,796 gal/mi-in.

Mix
Short haul (10 mi) = 766 x 10 x 2 x 0.0286 = 438 gal/mi-in.
Long haul (30 mi) = 766 x 30 x 2 x 0.0286 = 1,314 gal/mi-in.

Total transport energy
Short haul (63 + 280 + 438) = 781 gal/mi-in.
Long haul (63 + 2,796 + 1,314) = 4,173 gal/mi-in.

Processing energy
Aggregate
= 766 x 0.955 x 0.42 (Table B-1) = 307 gal/mi-in.

Asphalt
= 766 x 0.045 x 4.22 (Table B-1) = 145 gal/mi-in.

Total processing energy = 452 gal/mi-in.

Calorific energy
Asphalt
=766 x 0.045 x 266.9 (Table B-1) = 9,200 gal/mi-in.

4. Lean Concrete Base

Assumptions:

Local aggregate or recycled concrete = 15,000 Btu/ton
Aggregate hauled at 0.0182 gal/ton-mi (Table 14)
Short haul = 0 mi (plant at aggregate source)
Long haul = 30 mi
Lean concrete hauled at 0.0286 gal/ton-mi (Table 14)
Cement is hauled at 0.0182 gal/ton-mi (Table 14) (50 mi for both short and long haul)
Energy for batching concrete = 0.41 gal/yd^3 (average from Table 15)
Energy for placing concrete = 0.22 gal/yd^3 (average from Table 15)
250 lb cement/yd^3 = 0.058 tons cement/ton concrete (1 yd^3 = 2.15 ton)
Ton concrete/mi base = 14,080 ÷ 36 = 391 yd^3/mi-in. x 2.15 ton/yd^3 = 841 ton/mi-in.
Processing energy for cement = 7.232 x 10^6 Btu/ton

TABLE B-2 *continued*

Computations:		
1 ton concrete contains 0.91 ton aggregate + 0.058 ton cement + 0.032 ton water		
Construction energy		
Batching		
= 391 yd^3 x 0.41	=	160 gal/mi-in.
Placing		
= 391 yd^3 x 0.22	=	86 gal/mi-in.
Total construction energy	=	246 gal/mi-in.
Transport energy		
Cement (Short and long haul)		
= 841 x 0.058 x 50 x 2 x 0.0182 (Table 14)	=	89 gal/mi-in.
Aggregate		
Short haul (mixer at source)	=	0
Long haul = 841 x 0.91 x 1.05 x 30 x 2 x 0.00182 (Table 14)	=	878 gal/mi-in.
Concrete		
Short haul (10 mi) = 841 x 10 x 2 x 0.0286 (Table 14)	=	481 gal/mi-in.
Long haul (30 mi) = 841 x 30 x 2 x 0.0286 (Table 14)	=	1,443 gal/mi-in.
Total transport energy		
Short haul (89 + 0 + 481)	=	570 gal/mi-in.
Long haul (89 + 878 + 1,443)	=	2,410 gal/mi-in.
Processing energy		
Aggregate		
= 841 x 0.91 x 0.11 (Table B-1)	=	84 gal/mi-in.
Cement		
= 841 x 0.058 x 52.03 (Table B-1)	=	2538 gal/mi-in.
Total processing energy	=	2622 gal/mi-in.
5. Road-Mixed, Cement-Treated Subgrade		
Assumptions:		
Subgrade to be treated with 6% cement. Amount cement required: 14,080 yd^2 ÷ 36 x 2 ton/yd^3 x 0.06 = 47 ton/mi-in. Construction energy: 33 Btu/yd^2-in. per pass (4) x 9 passes = 300 Btu/yd^2-in.		
Computations:		
Construction energy		
300 Btu/yd^2-in. = 0.00216 gal/yd^2-in. 14,080 x 6 x 0.00216	=	182 gal/mi-in.
Transport energy		
Haul cement = 47 x 50 x 2 x 0.0182 (Table 14)	=	86 gal/mi-in.
Processing energy		
Cement = 45 x 52.03 (Table B-1)	=	2,445 gal/mi-in.

TABLE B-3
DETAILS OF ASSUMPTIONS AND COMPUTATIONS FOR TABLE 20

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1. Asphalt Concrete

Assumptions:

Composition of hot-mixed asphalt concrete HMAC --5% asphalt (mix basis)
Aggregate
- 60% crushed stone
- 35% natural sand
- 5% filler

} Total 95% of mix

Asphalt cement is hauled 50 mi to the plant
Aggregate is hauled 10 mi to plant for short haul and 100 mi to plant for long haul (aggregate contains 5% moisture when hauled and when introduced into dryer; initial temperature is 70°F; temperature of mix at discharge is 300°F)
Asphalt concrete is hauled an average distance of 7.5 mi for short haul and 40 mi for long haul (compacted density of the asphalt concrete is 145 lb/ft^3)

All energy computed on basis of equivalent gallons of diesel fuel at 139,000 Btu/gal

Computations:

Asphalt concrete required for 1 mi pavement
145 lb/ft^3 x 27 = 3,915 lb/yd^3 = 108.75 lb/yd^2-in.
14,080 yd^2 x 108.75 ÷ 2,000 = 765.6 ton/mi-in.

Asphalt cement
765.6 x 0.05 = 38.28 ton/mi-in.

Aggregate
= 765.6 x .95 = 727.3 total ton/mi-in.
Coarse aggregate = 436.4 ton/mi-in.
Sand = 254.5 ton/mi-in.
Filler = 36.4 ton/mi-in.

Construction energy
For heating and drying aggregate (exclude filler)
= 690.9 ton x 1.98 (from Table 16) = 1,368 gal/mi-in.
For heating filler (assume 1 gal/ton) = 36 gal/mi-in.
Total for heating and drying aggregate = 1,404 gal/mi-in.

For operating asphalt plant
= 765.6 ton x 19,800 Btu/ton (Table 17) ÷ 139,000 = 109 gal/mi-in.

For laydown and compacting HMAC
= 765.6 ton x 16,700 Btu/ton (4) ÷ 139,000 = 92 gal/mi-in.

Total construction energy = 1,605 gal/mi-in.

Transport energy
For hauling asphalt cement
= 38.28 ton x 50 mi x 2 x 0.0182 = 70 gal/mi-in.

For hauling aggregate
Short haul: 727.3 ton x 1.05 (5% moisture) x 10 mi x 2 x 0.0182 = 278 gal/mi-in.
Long haul: 727.3 ton x 1.05 (5% moisture) x 100 mi x 2 x 0.0182 = 2,780 gal/mi-in.

For hauling HMAC to job site
Short haul: 765.5 ton x 7.5 mi x 2 x 0.0286 = 328 gal/mi-in.
Long haul: 765.6 ton x 40 mi x 2 x 0.0286 = 1,752 gal/mi-in.

Total transport energy
Short haul = 676 gal/mi-in.
Long haul = 4,602 gal/mi-in.

Processing energy
38.28 ton asphalt cement x 4.22 gal/ton (Table B-1) = 162 gal/mi-in.
436.4 ton crushed aggregate x 0.42 gal/ton (Table B-1) = 183 gal/mi-in.
254.5 ton sand x 0.11 gal/ton (Table B-1) = 28 gal/mi-in.
36.4 ton filler x 0.42 gal/ton (Table B-1) = 15 gal/mi-in.

Total processing energy = 388 gal/mi-in.

Calorific energy
38.28 ton asphalt cement x 266.9 gal/ton (Table B-1) = 10,220 gal/mi-in.

TABLE B-3 *continued*

2. Plain Concrete

Assumptions:

PCC composition (materials in 1 yd^3)
Cement = 564 lb = 0.282 ton/yd^3
Coarse aggregate = 2,000 lb = 1.000 ton/yd^3
Sand = 1,154 lb = 0.577 ton/yd^3
Water = 282 lb = 0.141 ton/yd^3

Amount each material for 1 mi/in. thickness
Cubic yards required = 14,080 yd^2 ÷ 36 = 391.1 yd^3/mi-in.

Cement = 391.1 x 0.282 = 110 ton/mi-in.
Coarse aggregate = 391.1 x 1.0 = 391 ton/mi-in.
Sand = 391.1 x 0.577 = 226 ton/mi-in.
Total = 391.1 x 2 = 782 ton/mi-in.

Computations:

Construction energy
Batch concrete = 391.1 x 0.41 gal/yd^3 (Table 15) = 160 gal/mi-in.
Place and consolidate concrete
= 391.1 yd^3 x 0.22 gal/yd^3 (average from Table 15) = 86 gal/mi-in.
Total construction energy = 246 gal/mi-in.

Transport energy
Haul cement = 110 x 50 mi x 2 x 0.0182 (Table 14) = 200 gal/mi-in.
Haul coarse aggregate
Short haul = 391 x 10 mi x 2 x .0182 = 142 gal/mi-in.
Long haul = 391 x 100 mi x 2 x 0.0182 = 1,423 gal/mi-in.
Haul sand
Short haul = 226 x 10 mi x 2 x 0.0182 = 82 gal/mi-in.
Long haul = 226 x 100 mi x 2 x 0.0182 = 823 gal/mi-in.
Haul concrete
Short haul = 782.2 ton x 7.5 mi x 2 x 0.0286 (Table 14) = 336 gal/mi-in.
Long haul = 782.2 ton x 40 mi x 2 x 0.0286 (Table 14) = 1,790 gal/mi-in.
Total transport energy
Short haul (200 + 142 + 82 + 336) = 760 gal/mi-in.
Long haul (200 + 1,423 + 823 + 1,790) = 4,236 gal/mi-in.

Processing energy
Cement = 110 x 52.03 (Table B-1) = 5,723 gal/mi-in.
Coarse aggregate = 820 x 0.42 (Table B-1) = 164 gal/mi-in.
Sand = 226 x 0.11 (Table B-1) = 25 gal/mi-in.
Total processing energy = 5,912 gal/mi-in.

TABLE B-3 *continued*

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3. Reinforced Concrete

Assumptions:

Pavement thickness = 9 in.
Longitudinal steel: No. 4 bars at 12-in. spacing
Transverse steel: No. 2 bars at 6-in. spacing
Dowels: 1⅛-in. diam., 18-in. long, 1 ft on centers, 48-ft spacing; total no. = 2,640/mi
All steel hauled 50 mi to job

Computations:

Weight of Steel
Longitudinal: 24 x 5,280 ft = 126,700 ft x 0.668 ÷ 2,000 = 42.3 ton/mi
Transverse: 10,560 lengths x 24 ft x 0.167 ÷ 2,000 = 21.2 ton/mi
Dowels: 2,640 x 6.251 lb/dowel ÷ 2,000 = 8.3 ton/mi
Total weight = 71.8 ton/mi

Transport energy for steel
71.8 ton x 50 x 2 x 0.0182 ÷ 9 = 15 gal/mi-in.

Processing energy for steel
Longitudinal: 126,700 ft x 8,016 Btu/ft (Table 9) ÷ 139,000 ÷ 9 = 812 gal/mi-in.
Transverse: 10,560 x 24 x 2,004 Btu/ft (Table 9) ÷ 139,000 ÷ 9 = 406 gal/mi-in.
Dowels: 8.3 ton x 24 x 10^6 Btu/ton ÷ 139,000 ÷ 9 = 159 gal/mi-in.
Total processing energy for steel = 1,377 gal/mi-in.

Totals for reinforced concrete
Construction energy (same as plain concrete) = 246 gal/mi-in.

Transport energy
Short haul (760 + 15) = 775 gal/mi-in.
Long haul (4,236 + 15) = 4,251 gal/mi-in.

Processing energy = 5,912 + 1,377 = 7,289 gal/mi-in.

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