R.E. Schamber

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE

54

RECYCLING MATERIALS FOR HIGHWAYS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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RECYCLING MATERIALS FOR HIGHWAYS

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

AREAS OF INTEREST:
- PAVEMENT DESIGN
- BITUMINOUS MATERIALS AND MIXES
- CONSTRUCTION
- GENERAL MAINTENANCE

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1978

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 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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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 and usefulness to design engineers, materials technologists, and others seeking information on the potential use of recycled materials in design, construction, rehabilitation, and maintenance of pavements, bases, and other components of the highway system. Detailed information is presented on procedures for pavement recycling.

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.

There has been growing interest and activity in the area of recycling materials for pavements, bases, and other highway components. This has been brought about by an awareness of the need to conserve energy, natural resources, and funds, and to reduce disposal problems. This report of the Transportation Research Board reviews concepts and field experience for application of recycling materials in highways. Primary emphasis is on pavements, but experience with recycling other items, such as guardrail components and sign blanks, is also reviewed. Research and development needs for advancement of recycling are identified.

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 researchers 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.

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ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Paul E. Irick, Assistant Director for Special Projects. 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 Gay I. Leslie.

Special appreciation is expressed to Jon A. Epps, Associate Research Engineer, Texas Transportation Institute, who was responsible for collection of data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of A. G. Calvert, Office of Materials, Iowa Department of Transportation; James A. Jackson, Owner, Jim Jackson—Contractor, Little Rock, Ark.; Robert H. Joubert, District Engineer, The Asphalt Institute; C. O. Leigh, Maintenance Engineer, Virginia Department of Highways and Transportation; Richard A. McComb, Highway Research Engineer, Office of Research, Federal Highway Administration; John J. Schultz, Highway Engineer, Office of Highway Operations, Federal Highway Administration.

Bob H. Welch, Associate Engineer of Materials and Construction, Transportation Research Board, assisted the Special Projects Staff and the Topic Panel.

Information on current practice was provided by many highway agencies, recycling contractors, equipment manufacturers, and suppliers. Their cooperation and assistance were most helpful.

RECYCLING MATERIALS FOR HIGHWAYS

SUMMARY

One solution to some of the problems facing transportation administrators is to recycle existing materials for construction, rehabilitation, and maintenance. Recycling can help stabilize costs, conserve scarce material resources, and reduce the amount of energy required. Recycleable materials include those used in both rigid and flexible pavements, guardrail, signs, sign posts, and delineator posts.

Industry has recycled glass, aluminum, steel, and paper for years. Highway materials have also been recycled for a number of years. Pavements and bases have been reused, and industrial byproducts such as slag, fly ash, and mine tailings have been used in some areas. Recently, however, the importance of recycling highway materials has increased tremendously.

Pavement recycling is usually categorized by (a) the procedure used, (b) type of materials, and (c) the structural benefit to be gained. The organization of this synthesis is based on the recycling procedure. *Surface recycling* is a reworking of the top inch of a pavement. *In-place surface and base recycling* includes pulverization of more than 1 in. (25 mm) followed by reshaping and compaction. *Central-plant recycling* requires removal of material from the roadway, mixing in a plant, and laydown and compaction.

Surface recycling is the most popular form of recycling and is widely used for treating raveling, rutting, flushing, and corrugations. Some of the techniques used for surface recycling are: heater-planer, heater-scarifier, hot millers, cold planers, and cold millers. New York DOT monitored the removal of asphaltic concrete using the heater-planer, hot milling, and cold milling. Of interest were air and noise pollution, depth of heat penetration, physical properties before and after, skid resistance, production rate, depth precision, and bond between the new and old surfaces. The comparison is discussed in Chapter Two.

In-place surface and base recycling has been performed in most states using bulldozers, vibratory compactors, rollers, etc., to crush old pavements. Recent refinements include development of pulverizing equipment and processing techniques using a traveling hammer-mill. Stabilizers such as lime, cement, asphalt, and other chemicals have been used. A major advantage of in-place recycling is the ability to improve the pavement load-carrying ability with minimum change of roadway section. Both state transportation agencies and contractors have had considerable experience with in-place recycling.

Recycling of asphaltic pavement surfaces dates back to 1915; however, very little experimentation was done from that time to 1974. Recently, portlant cement

concrete pavements have been recycled experimentally back to portland cement concrete.

Central-plant recycling processes using heat and asphalt cement stabilizer are estimated to attain about 10 percent of the hot-mix market in 3 to 5 years. Both indirect and direct flame heating will be used.

Several states have completed recycling projects that used either reprocessed portland cement concrete or bituminous materials as aggregate for base. In some cases, bituminous and concrete materials were recycled as a single operation. Removing reinforcing steel before the material is processed through a crusher has not been a serious problem. Automatic pavement breakers, air chisels, cranes and balls, and similar equipment have been used to break up concrete pavements.

Bituminous pavements usually can be broken up by a grader scarifier or by a ripper pulled by a bulldozer. Further break-up can be done with a compactor or other equipment before the material is picked up and hauled to a central location for crushing and mixing. However, on most jobs the old pavements were crushed at a central location.

Significant quantities of guardrails and sign blanks have been recycled. Some culverts, motor oil, and posts have also been recycled or reused. Other available byproducts or waste products include fly ash, sulfur, mining waste, slag, glass, tires, and incinerator residue.

Other findings are:

- Pavement recycling and the use of waste material can reduce aggregate requirements in some areas.
- Specialized pulverization equipment is available for in-place recycling operations.
- Hot central-plant recycling of asphaltic concrete has been accomplished by several processes without air pollution.

Future research should: study air pollution associated with recycling asphaltic pavement materials, develop guidelines for the decision-making process concerned with recycling, develop data on costs and energy consumption for recycling operations, study the properties of recycled mixes, develop improved or new equipment, test and evaluate modifying agents, develop modifiers that will soften asphalt, improve resistance to water-caused deterioration, define quality control requirements for recycling construction, and establish strength coefficients for recycled materials based on pavement performance.

CHAPTER ONE

INTRODUCTION

Expansion, rehabilitation, and maintenance of any transportation system depend on fiscal resources to finance the system; the technology to plan, design, construct, and maintain the facility in an economic manner; supplies of aggregate and binder; and equipment and manpower resources with which to construct and maintain the facilities.

Federal, state, and local agencies responsible for transportation facilities are faced with a number of problems, including:

1. A reduction in available funds for transportation facilities caused by inflation, decline in tax base, decline or leveling in revenue from fuel tax, fiscal demands of other programs, and other factors.
2. Materials supply problems resulting from depletion of sources near the point of use; unavailability because of zoning laws; increased haul distances and associated transportation costs; strict environmental codes limiting production in certain areas and requiring major expenditures for air and water quality, noise control, and pit and quarry restoration; and use of potential construction materials for other purposes.
3. Equipment availability problems resulting from reduced budgets, the high cost of new equipment, and other factors.
4. Manpower problems resulting from fiscal constraints on wages, which often create a deficiency of trained equipment operators and qualified engineering-oriented employees; labor-management problems; and the need to increase productivity to provide for an economical operation.
5. Energy problems associated with fuel availability and cost and the urgent need to reduce energy consumption.

Because of these problems and others, there is an urgent need to optimize the use of aggregates, binders, equipment, manpower, energy, and funds from planning, design, construction, rehabilitation, and maintenance standpoints.

One solution to some of the transportation problems outlined is to reuse or recycle existing materials for construction, rehabilitation, and maintenance purposes. Recycling of pavement materials (such as asphaltic concrete and portland cement concrete), highway materials (such as guardrails and sign blanks) and nonhighway materials (such as industrial, mineral, and domestic wastes) offers several advantages over use of conventional materials. Among the major benefits are *conservation* of aggregates, binders, metals, and energy and *preservation* of the environment and existing highway geometrics.

Conservation of aggregate and binder is important. Although the United States has an abundant supply of source materials for production of quality aggregates for the foreseeable future (*1, 2*), distribution of these sources does not always coincide with location of need. Thus, it has become necessary to haul aggregates over large distances. This has escalated the cost and the energy consumed in constructing transportation facilities. Recycling the aggregate in the old pavement and using by-products and waste products for reconstruction, rehabilitation, or maintenance purposes will decrease aggregate demand and extend the supply of construction aggregate at a time when sources (particularly near urban areas) are being depleted because of high use, mining restrictions, environmental protection regulations, and appreciating land values.

Conservation of binders is another important advantage afforded by recycling. For example, pulverization and reuse of asphaltic concrete normally requires about 1 to 3 percent additional asphalt, whereas a new asphaltic concrete mixture requires about 6 percent. This saving of about 10 gallons of asphalt per ton (4 L/Mg) of asphaltic concrete produced can contribute to the nation's fuel conservation program. Asphalt can be used directly as fuel for electrical power plants, for utilities at refineries, or can be converted to other hydrocarbons for use in aircraft, automobiles, and steel manufacturing.

The conservation of metals is practiced in several states by recycling guardrails, sign blanks, delineator posts, and sign posts. Certainly, other items associated with traffic control can be recycled. Recycling of highway litter is technically feasible but presently can not be economically justified.

The conservation of energy is apparent in recycling operations if one considers the reduced hauling required for aggregates and the reduced hauling and production energy required for the binder in recycled pavement materials. Energy savings of recycling operations, however, should be determined on a job-to-job basis.

Recycling can contribute to environmental preservation by reducing the amount of new materials required for highway use. Thus, a corresponding reduction is possible in environmental problems of mining the new material and manufacturing the products, in addition to avoiding the problems associated with disposition of the old pavement.

The maintenance of highway geometrics can be achieved relatively easily by pavement recycling. For multilane facilities, only the distressed lane need be recycled. Full-width overlays are not required to promote drainage. Vertical clearance problems caused by overlays at bridges, signs, and tunnels can be overcome by strengthening the existing surface, base, or subgrade. Vertical control problems with drainage facilities, such as gutter flow lines, curb height, inlet capacity, and manholes, are reduced when recycling operations are used instead of overlays.

TABLE 1

SUMMARY OF STATE RECYCLING ACTIVITIES (SEPTEMBER 1976)

STATE	Pavement Recycling								Central Plant			Guardrail (linear ft.)
	Surface			In-Place								
	No. of Project	Lane Miles	Depth (in.)	No. of Project	Tons (1000's)	Lane Miles	Depth (in.)	No. of Project	Tons	Lane-Miles	Depth (In.)	
ALABAMA	0			0				0				Sm. Amt.
ALASKA	0			0				0				0
ARIZONA	Many		3/4									
ARKANSAS	1	0.67	1	9		77	1	0				82,122(2)
CALIFORNIA	75	88.5	3/4	1		6	10	1		12	(3)	6,200
COLORADO	0			1		40	3	0				5,000
CONNECTICUT	3	11.4	1	0				0				100,000
DELAWARE		N.A.				N.A.		0				N.A.(1)
FLORIDA	14	41.6										528,000
GEORGIA	2	2.6	3/4	0				0				40,000
HAWAII	0			0				0				0
IDAHO	3	75	1/2-3/4	0				0				N.A.
ILLINOIS	N.A.			40		271	6	0				53,600
INDIANA				1		6.9	6(5)					
IOWA	0			0				5	102,864			N.A.(6)
KANSAS (16)	0			0				0				
KENTUCKY												
LOUISIANA	1	20.4	3/4	0				0				27,315
MAINE	0			3		10.8	(9)	0				
MARYLAND		Sm.Amt.		0				0				0
MASSACHUSETTS	10	30	1.5	4		7	15	0				8,000
MICHIGAN	0			8(10)	370		5	0				180,000
MINNESOTA	0			0				0				40,000
MISSISSIPPI	0			0				0				13,257
MISSOURI	N.A.	18(11)		0				0				25,640
MONTANA												29,000
NEBRASKA												2,000
NEVADA	46	62.2	1			96.2	8	1				2,500
NEW HAMPSHIRE	1	5	1	1		0.75	3			2	4	10,000
NEW JERSEY	2	N.A.		0				0				N.A.
NEW MEXICO	Many	N.A.	3/4									
NEW YORK	0			0				0				50,000
NORTH CAROLINA				0								
NORTH DAKOTA	0			0				0				0
OHIO	0			0				0				508,000
OKLAHOMA												600,000
OREGON				1	8		6					800,000
PENNSYLVANIA												300,000
RHODE ISLAND	0			0				0				20,000(14)
SOUTH CAROLINA	0			N.A.				0				N.A
SOUTH DAKOTA	0			0				3	475,118		8(15)	100,000
TENNESSEE	0			0				0				
TEXAS (17)	3	10.8	1	1		0.8	1.5	3		5.8	2	84,000
UTAH	18	100	1/4-1	10		20	3± 1	1	400			15,000
VERMONT	0			1		4	3					0
VIRGINIA	2	3	1/4	2	1.3		6					55,900
WASHINGTON	1	5	1									25,900
WEST VIRGINIA	0			0				0				300,000
WISCONSIN (19)	3	12	1	10		111	8	0				65,000
WYOMING (20)	1	15	3/4	0				0				4,700

(1) Quantity not available but material has been recycled
(2) Includes 64,962 linear ft straightened and galvanized by contract
(3) Central plant recycling consisted of 12 lane mi. of 4.8 in. of lean concrete base, 12 lane mi. of 4.8 in. of cement treated base, 24 lane mi. of 6.3 in. of class 3 aggregate base
(4) Rubber asphalt used as stress-relieving interface; 1976 specification allows fly ash as a partial replacement for cement in pavements and structures; experimental projects with slag; sign blanks recycled through a state designed cleaner; some guardrail posts and anchor systems occasionally salvaged; some structural steel used in repair situations
(5) A ten ft shoulder was recycled; unsatisfactory results obtained
(6) Routine practice for a number of years, quantities not available
(7) Old motor oil used as supplemental fuel in hot mix plants
(8) Old tires from skid testing used for front tires on mowers
(9) Two lane mi, 12 in. depth; 3.3 lane mi, 4 in. depth; 5.5 lane mi, 8 in. depth
(10) Primarily interstate shoulder rehabilitation but quantity includes 4.5 mi. of roadway

Sign Blanks (Sq. Ft.)	Culverts (Linear ft)	Motor Oil Gallon	Sign Posts	Delin. Posts	Glass (ton)	Tires (ton)	Mining Wastes (ton)	Fly Ash (ton)	Slag (ton)
Sm. Amt.	0	0						Sm. Amt.	Sm. Amt.
0	0	0			0	0	0	0	0
325,000	0	0			0	0	0	0	0
5,000	0	0			0	9	0	0	2,720,000
5,000	6,000	6,000			0	0	0	0	0
105,897	N.A.	0			0	0	0	0	0
500,000	6,000	43,500			0	0	0	0	0
480,000			N.A.(4)			N.A.(4)		N.A.(4)	N.A.(4)
4,000	0	0			0	0	0	0	0
N.A.	N.A.	0			0	9	500,000	0	700,000
1,100,000	0	0			0	24	0	56,700	111,900
1,000,000									
N.A.(6)	N.A.(6)	N.A.(6)			10		N.A.	950	
	N.A.	N.A.(7)				N.A.(8)	$3\text{-}5 \times 10^6$	0	
175,000	0	0			0	0	0	0	0
						124			
0	0	0			0	0	0	Sm. Amt.	1,000,000
Sm. Amt.						5-10			
Sm. Amt.	0	0	Sm. Amt. (21)		0	0	0	0	0
85,000	115,000	50,000			0	0	250,000	12,000	0
225,000	1,000	0			0	Sm. Amt	0	0	347,484
500	0	0			0	0	600,000	0	350,000
				11,675					
33,000	2,000								
40,000	400	20,000							
0	0	0			0	0	0	0	0
N.A.	Sm. Amt.	0			0	0	0	N.A.	N.A.
39,000	0	0			0	0	Lg. Amt.	Sm. Amt.	N.A.
150,000	N.A.	0						40,000	
164,000	5,000	0			200,000(12)	0	0	18,000	5,000,000
50,000							Sm. Amt.		
4,000	5,000	14,000			Sm. Amt.	Sm. Amt.	Sm. Amt.	0	9,000 (13)
850,000							2,200,000	300,000	30,500,000
8,000(14)					0	0	0	0	0
N.A.	N.A.	0	N.A.		0	0	0	N.A.	0
1,000,000	0	0			0	0	0	0	750,000
2,880,000	80,000	N.A.		20,000	0	116	0	3,300	600,000
11,000	0	0		5,000	0	20(18)	8,000,000	0	2,000,000
0	0	0			50	3,000	0	0	0
210,000	4,000	20,000			0	0	0	0	0
				637			500,000		
70,000	0	5,019			0	0		265,000	160,000
50,000	1,900	0	N.A.	N.A.	0	0	0	850	0

(11) State owns two heater planers and performs work mainly in urban areas at rate of about 25,000 sq yd annually
(12) Used in roadway embankment
(13) 9,000 tons per year recycled; 60,000 lbs. of paper recycled per year
(14) Quantity recycled 1976
(15) Base and subbase taken from one roadbed mixed with lime and used as base in new roadbed
(16) Kansas has recycled 5,000 tons of wet bottom boiler slag
(17) Texas has recycled 12,000 55-gal drums
(18) 20 lane mi on two projects
(19) Wisconsin has recycled 4,000,000 tons of top soil, 800 linear ft of storm sewer, 750 linear ft of fencing, 3,000 linear ft of chain link fence, 800 linear ft of aluminum railing, 800 light poles, drainage structure castings, underdrain pipe, signal cabinets, lighting luminaires, electrical conduit reflectors
(20) Wyoming has recycled 78,205 linear ft of fencing
(21) Equipment is being purchased

Recycling of material has been practiced for years in the glass, paper, aluminum, steel, and other industries. These industries have used recycling because they recognized that finite amounts of raw materials exist with which to make their products. Furthermore, the economics of these industries have made recycling competitive with production of products from raw materials.

Recycling in transportation has also been practiced on a small scale for years. Reuse of surfacing materials as unstabilized base has been practiced extensively. Recycling of pavements has been practiced since 1915. Industrial by-products such as slag, fly ash, and mine tailings have also been used in selected areas of the country. The importance of recycling in the highway field has increased tremendously in the last three years. The concepts of conservation and preservation and the arrival of the proper economic atmosphere have stimulated this growth.

The majority of this synthesis is directed towards recycling or reusing pavement materials; the remainder is directed towards recycling of other highway materials and recycling of off-highway materials.

As a starting point, an extensive literature review was conducted, and a questionnaire was circulated to state highway and transportation departments to define the types of materials currently being recycled. The literature review was sponsored in part by the Texas State Department of Highways and Public Transportation. Forty-nine of the 50 States responded to the questionnaire, with the results given in Table 1.

CHAPTER TWO

RECYCLING OF PAVEMENT MATERIALS

Recycling or reuse of existing pavement materials for pavement rehabilitation, reconstruction, and maintenance is not a new concept. A wide variety of recycling approaches has emerged since the 1930s. Categorization of recycling approaches is usually based on (a) the recycling procedure used, (b) the type of paving materials to be recycled and the end products they are to produce, or (c) the structural benefit to be gained from the recycling approach. Each of these categories has its own merit in describing the purpose and applicability of a given type of recycling. A categorization based on the recycling procedure has been used for this synthesis. Figure 1 defines the framework within which the present types of pavement recycling are defined.

Definitions for these recycling categories have been prepared by the Federal Highway Administration Demonstration Project No. 39 Technical Advisory Committee (*3*), a joint National Asphalt Pavement Association–Asphalt Institute committee (*4*), Asphalt Recycling and Reclaiming Association (*5*), National Cooperative Highway Research Program (*6*), U. S. Army Engineer Waterways Experiment Station (*7*), and Navy Civil Engineering Laboratory (*8*). The following definitions are based on these suggestions together with those of the synthesis panel members.

Surface recycling—Reworking of the surface of a pavement to a depth of less than about 1 in. (25 mm) by heater-planer, heater-scarifier, hot-milling, cold-planing, or cold-milling devices. This operation is a continuous, single-pass, multistep process that may involve use of new materials, including aggregate, modifiers, or mixtures.

In-place surface and base recycling—In-place pulverization to a depth greater than about 1 in. (25 mm), followed by reshaping and compaction. This operation may be performed with or without the addition of a stabilizer.

Central-plant recycling—Scarification of the pavement material, removal of the pavement from the roadway prior to or after pulverization, processing of material with or without the addition of a stabilizer or modifier, and lay-down and compaction to desired grade. This operation may involve addition of heat, depending on the type of material recycled and the stabilizer used.

As shown in Figure 1 and as previously defined, the recycling process can include addition of heat or can be performed in the absence of heat. Definitions currently used by the Federal Highway Administration are based in part on those developed by the joint National Asphalt Pavement Association–Asphalt Institute committee. The definitions include a delineation of (a) hot-mix asphaltic pavement recycling, (b) cold-mix asphaltic pavement recycling, (c) asphaltic pavement surface recycling and (d) portland cement concrete pavement recycling (*9*). Table 2 gives the advantages and disadvantages of each recycling category.

Before describing the equipment and the processes involved in the various categories of recycling, it is necessary

to recognize that pavement recycling is one of many rehabilitation or maintenance alternatives from which the engineer must select (Fig. 2). Selection of an alternative depends on the pavement distress, the probable causes, economics, and design information. The following factors should be considered:

1. History of the pavement maintenance requirements and costs.
2. History of pavement performance.
3. Horizontal and vertical geometric controls.
4. Environmental factors.
5. Traffic.

Once recycling has been selected as a possible rehabilitation alternative, the process of selecting a specific recycling operation begins (Fig. 3). Limited laboratory and field tests should be performed to establish the material resources available in the pavement and the stabilizers that can be used with these materials. From this preliminary information, potential recycling alternatives can be selected and preliminary pavement designs and economic analyses can be developed. Based on these data, the most promising recycling alternatives are selected, detailed laboratory tests

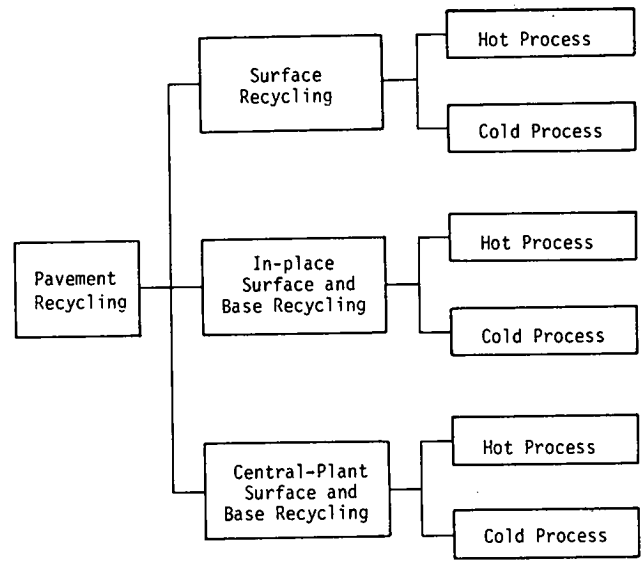


Figure 1. Categorization of recycling approaches based on recycling procedures.

TABLE 2

MAJOR ADVANTAGES AND DISADVANTAGES OF RECYCLING CATEGORIES

Recycling Categories	Advantages	Disadvantages
Surface	· Reduces reflection cracking · Promotes bond between old pavement and thin overlay · Provides a transition between new overlay and existing gutter, bridge, pavement, etc. that is resistant to raveling (eliminates feathering) · Reduces localized roughness · Treats a variety of types of pavement distress (raveling, flushing, corrugations, rutting, oxidized pavement, faulting) at a reasonable cost · Improved skid resistance · Minimum disruption to traffic	· Limited structural improvement · Heater-scarification and heater-planning have limited effectiveness on rough pavement without multiple passes of equipment · Limited repair of severely flushed or unstable pavements · Some air quality problems · Vegetation close to roadway may be damaged · Mixtures with maximum size aggregates greater than 1-inch cannot be treated with some equipment
In-place	· Significant structural improvements · Treats all types and degrees of pavement distress · Reflection cracking can be eliminated · Frost susceptibility may be improved · Improve ride quality	· Quality control not as good as central plant · Traffic disruption · Pulverization equipment repair requirement · Cost · Cannot be easily performed on PCC pavements
Central-plant	· Significant structural improvements · Good quality control · Treats all types and degrees of pavement distress · Reflection cracking can be eliminated · Improved skid resistance · Frost susceptibility may be improved · Geometrics can be more easily altered · Better control if additional binder and/or aggregates must be used · Improve ride quality	· Increased traffic disruption · May have air quality problems at plant site

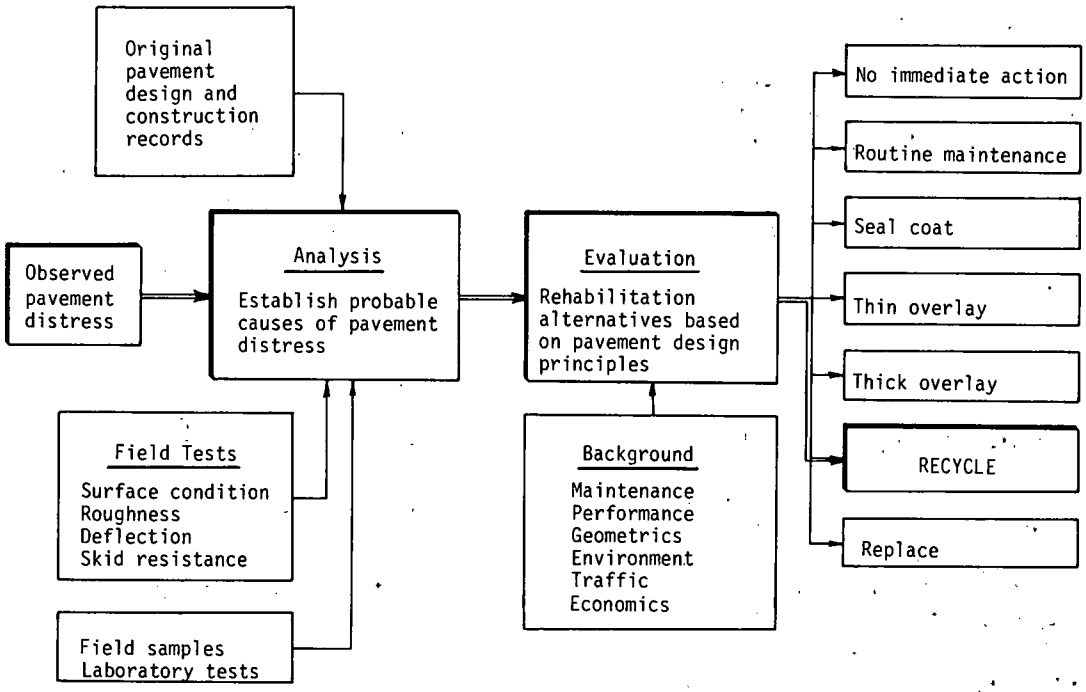


Figure 2. Recycling as a rehabilitation alternative.

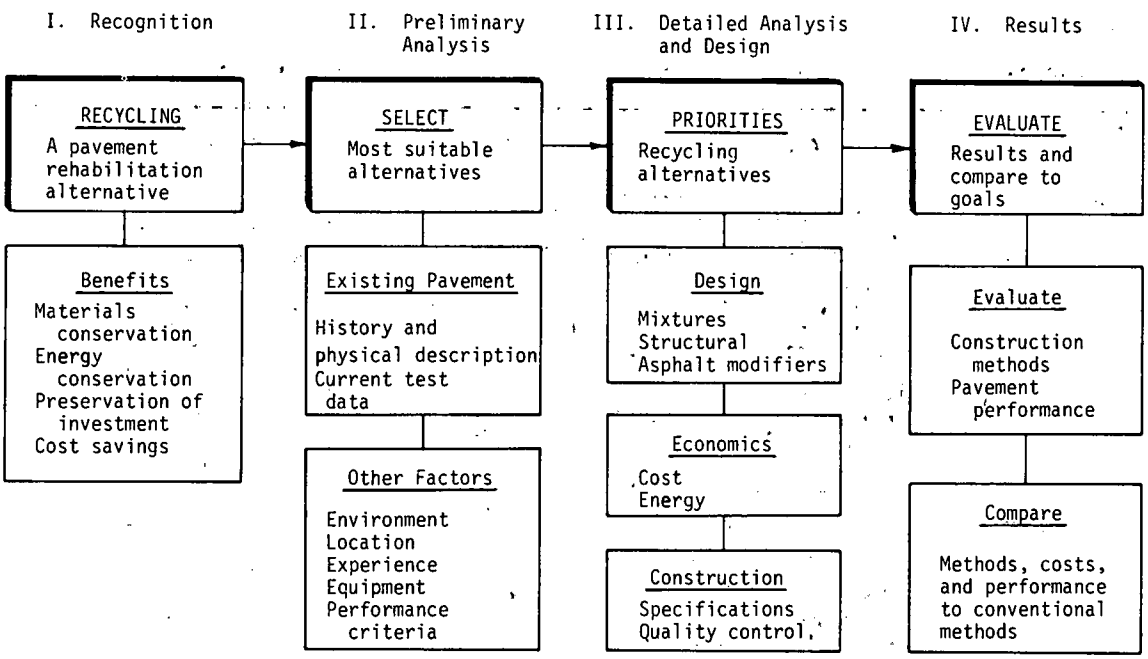


Figure 3. Selection of a recycling operation.

are performed to establish stabilizer contents, and the pavement section is designed. Energy requirements for the recycling operation should be determined and, if favorable, construction specifications prepared and the recycling operation performed. Finally, the performance of the recycled materials should be evaluated over a period of time together with in-place material properties determined by field and laboratory testing programs. These data should be used as feedback to the future selection of pavement rehabilitation alternatives. Details of the selection process described in the foregoing and shown in Figure 3 are contained in a report prepared under NCHRP Project 1-17, "Guidelines for Recycling Pavement Materials" (*6*).

CHAPTER THREE

SURFACE RECYCLING

Surface recycling differs from the other broad categories of recycling in that it involves reworking the surface of a pavement to a depth of less than 1 in. (25 mm) (unless multiple passes are made). Thus, surface recycling has a limited effectiveness in repairing rough riding or severly rutted roads or in significantly increasing the load-carrying capacity of the roadway (Table 2). However, surface recycling is presently the most popular form of recycling because at a reasonable cost it can treat a wide variety of pavement distress, including raveling, rutting, flushing, and corrugations. Additionally, data illustrate the usefulness of heater-scarification plus an overlay to reduce reflection cracking (*10*). Other advantages of surface recycling appear to be the ability to promote a bond between the old roadway and a thin overlay and to provide a transition between the new overlay and existing gutters, bridges, pavements, etc. The material removed by planing and milling can be reused in stabilized or unstabilized bases and shoulders and in stabilized surfaces.

The evolution of surface recycling equipment is not well documented; however, literature indicates that three of the original heater-planer units were developed in California in the 1930s (*11*). One unit was a heater, towed as a semitrailer behind a truck trailer, followed by an independent grader. A second unit was a combined heater and planer. A third unit was a heater mounted on a grader. The grader blade on this unit was replaced by a planer blade. The diesel oil-fired heater was pulled by the scarifier arms, and the solid rubber tires were cooled by water dripping from a front-mounted water tank. The blade could be rotated to deliver the cuttings inside of the rear wheels on either side. The cuttings were picked up by a front-end loader (*11*).

The first surface recycling machine that did not use heat apparently dates to about 1936 (*11*). This device used chisels to cut the cold roadway. Since the early days of cold surface recycling, techniques have been developed to grind the pavement with rotating drums equipped with cutting teeth.

Since 1930, a wide variety of recycling equipment has been developed and a number of innovative techniques established. For discussion purposes, this equipment and the associated techniques have been categorized into heater-planers, heater-scarifiers, hot-millers, cold-planers, and cold-millers (Fig. 4). Equipment manufacturers and contractors are listed in Appendix A.

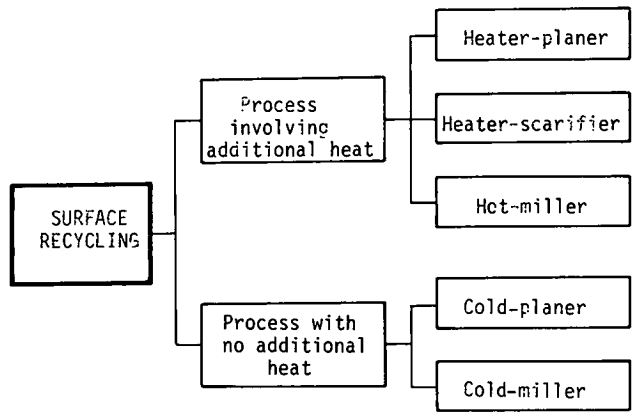


Figure 4. Surface recycling.

HEATER-PLANING

Heater-planers have been used primarily for maintaining pavement longitudinal grade and transverse cross slope. Other uses include removing pavement from bridges to reduce the dead weight; maintaining proper clearances in tunnels, at underpasses, and at sign bridges; removing improperly designed or constructed chip or slurry seals; and removing surface irregularities from rough pavements caused by instability, swelling clays, repeated maintenance activities such as crack sealing, etc.

It is a common practice to heat and plane a pavement prior to overlay. This activity will correct rutting problems, remove some of the pavement roughness, and provide a header cut, gutter cut, or keyway to prevent feathering of the hot mix. Any material that is removed from the roadway can be reused.

A unique application of the heater-planer is to use the heating units to aid in a corrective maintenance activity. For pavements with poor skid resistance, a layer of polish-resistant aggregate can be spread on the surface with a conventional seal-coat chip spreader. The heating unit then heats the pavement and is followed by a steel-wheel roller to embed the aggregate into the old pavement surface. This activity is particularly effective where flushing or bleeding is a problem.

Heater-planers are available that heat and plane the pavement with a single piece of equipment, such as the Cutler and Jim Jackson equipment. Others, such as that used by Payne, involve two pieces of equipment: a heating unit and a separate planing unit. Table 3 lists equipment features, cost information, and fuel consumption data where available. Costs for heating and planing a pavement to a ¾-in. (19-mm) depth range from about \$0.15 to \$0.60/yd^2 (\$0.18 to \$0.72/m^2), with fuel consumption for both heating and power within the range of 10,000 to 20,000 Btu/yd^2 (12 600 to 25 200 kJ/m^2). Production rates vary with the equipment used, the thermal properties of the asphaltic concrete being scarified, the pavement temperature prior to heating, and the depth of planing desired. Expected costs for heating, planing, traffic control

TABLE 3

EXAMPLES OF SURFACE RECYCLING EQUIPMENT—HEATER-PLANERS

Manufacturer	Equipment Features	Costs		Fuel				Comments
		$/yd²	Includes	Type	Quantity gal/yd²	BTU /yd²	Includes	
Asphalt Equipment, Inc.	heats and planes	0.15-0.28	equipment rental, fuel and labor to heat and plane	propane				fire horizontally, 3/4-inch removal
Cutler Helio-Planer	heats, planes, and elevates	0.50	equipment rental, fuel, labor, and elevation of material	propane diesel	0.2 0.02	18,200 2,800	heating, power unit	indirect heating, 250 sq yds per hr, 3/4-1 inch removal
Jim Jackson Heater-Planer	heats, planes, and elevates	0.40-0.60 for 1 in. thickness	equipment rental, fuel, labor and elevation of material	propane	0.15 for 3/4 in. cut	13,770	heating	direct heating, 800 sq yds per hr, 3/4-inch removal
Greenside MK III Road Planer	heats and planes							
Littleford*	heats and planes							
Payne Heater-Planer	heating unit separate from planer	0.40-0.60	heat, plane, clean-up, haul, and traffic control	diesel propane	0.11 0.11	20,000 9,000	heating and power unit	direct heating, 3,000 sq yds per day, 3/4-inch removal

*Equipment no longer manufactured.

required during the operation, and removal of the material from the pavement are on the order of $0.70 to $0.90/yd² per inch of depth ($0.33 to $0.42/m² per cm of depth). A heater-planer operation is shown in Figure 5.

HEATER-SCARIFYING

Recycling operations using the heater-scarifying approach take many forms. Figure 6 indicates several of the many possibilities that exist. The basic operations consist of preparing, heating, and scarifying the surface; adding additional materials if required; compacting; making final adjustments to manholes and drainage structures; and opening the facility to traffic.

Heater-scarifiers have also been used to remove pavement surface irregularities. Use of these units immediately before making an asphaltic concrete overlay offers some advantage. Pavement surface roughness can be removed to provide a smooth surface for a new wearing course and thereby eliminate or reduce the amount of leveling course required. The bond between the old pavement and a new asphaltic concrete overlay is also improved by use of the heater-scarifier or heater-planer immediately before an overlay.

Reflection cracking, which is a major consideration in overlay design, may be reduced by use of heater-scarifying

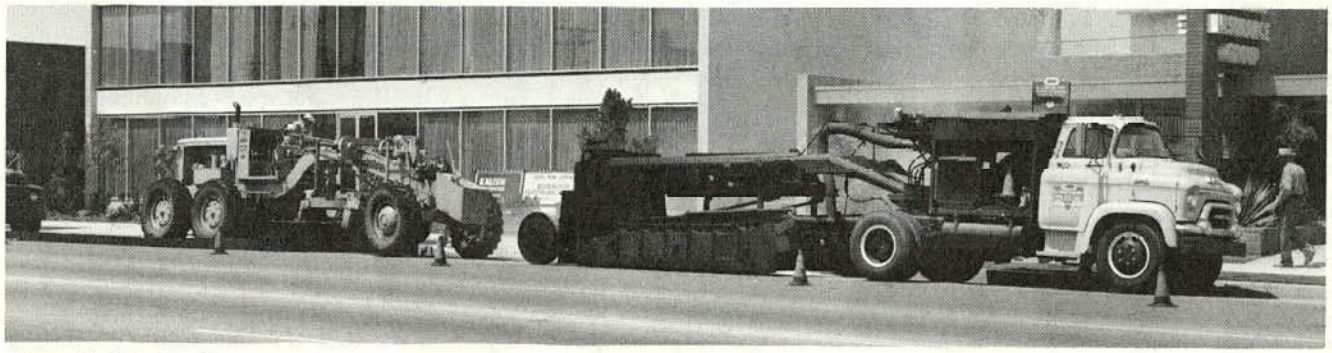


Figure 5. Heater-planer.

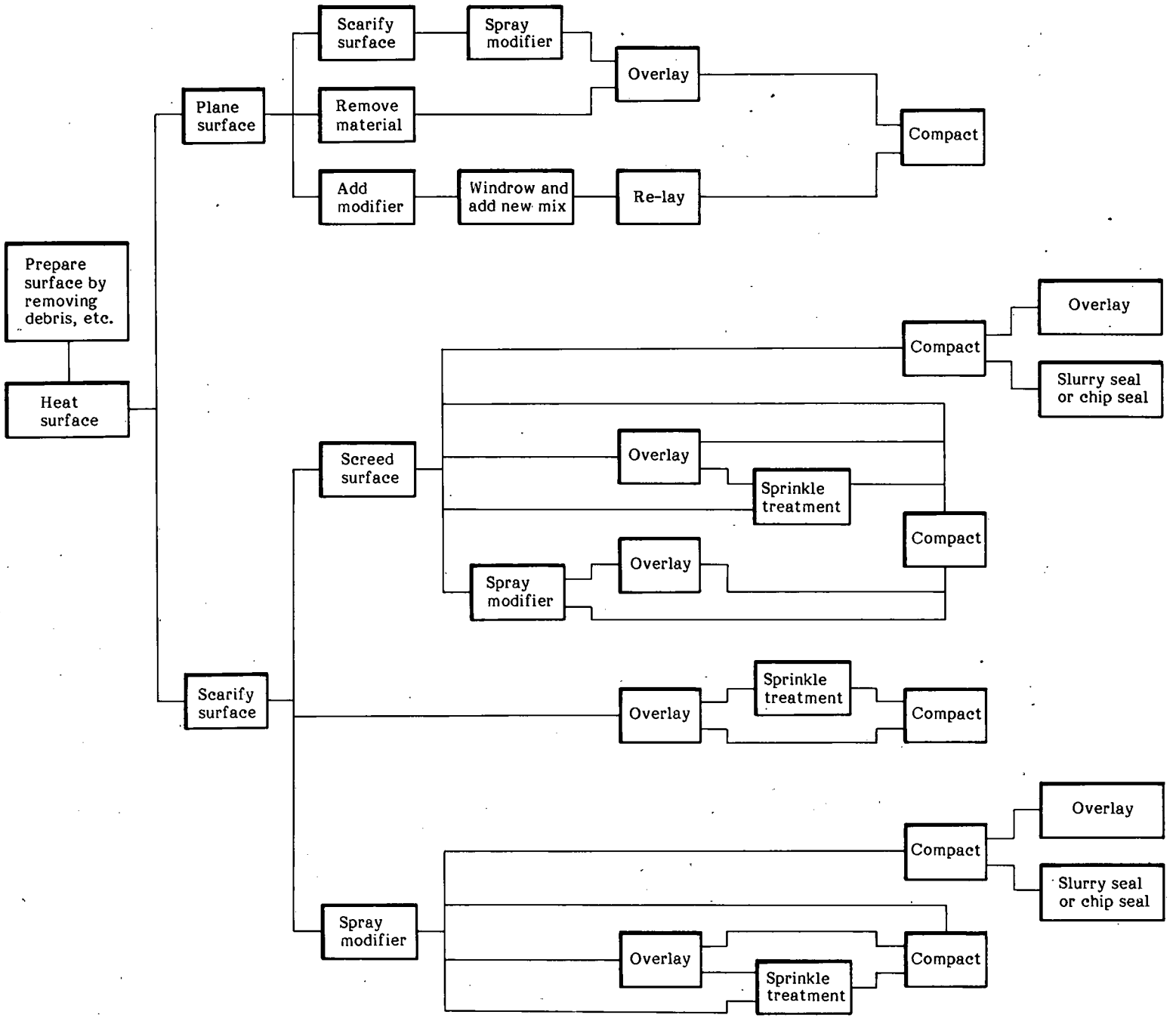


Figure 6. Recycling using the heater-scarifier.

prior to overlaying asphaltic concrete pavements. Documentation illustrates this advantage (*10*).

Many miles of highways in the United States and Europe have been recycled using one of the heater-scarifier approaches described. Agencies in Arizona, Arkansas, California, Florida, Illinois, Kansas, Maryland, Massachusetts, Nevada, New Mexico, Utah, and Wisconsin have been particularly active.

Heater-scarifying equipment varies in both appearance and design. Equipment presently used by Asphalt Equipment Incorporated and G. J. Payne has the ability to heat and scarify with a single unit. The equipment used by Jim Jackson can heat, scarify, and level the scarified mixture with a single unit. Some units operated by Jackson can spray and mix modifiers. The Cutler Repaver and Jumbo Repaver have the ability to heat, scarify, spray a liquid additive, add additional paving material, and mix and lay the resulting material. The Cutler equipment has a receiving hopper, conveyor system, and heavy-duty vibratory screed similar to those components on a conventional asphalt paver.

Heating systems, like those on the heater-planing devices, are either radiant-heat emitters or open-flame burners. These emitters or burners are enclosed by a hood that directs the heat onto the pavement surface. Carbide-tip steel blades on spring-mounted scarifiers or air-bag operated scarifiers are used to loosen and process the heated pavement. Steel scraper blades are often included with the heater-scarifiers to assist in leveling and to gather the excess material into a windrow to facilitate loading.

Table 4 lists equipment features, cost information, and fuel consumption data where available. Costs for heating and scarifying a pavement to a ¾-in. (19-mm) depth range from about \$0.15 to \$0.60/yd² (\$0.18 to \$0.72/m²). Costs are about the same as those for heater-planer operations. Fuel consumption appears to be on the order of 8,000 to 15,000 Btu/yd² (10 000 to 19 000 kJ/m²) for ¾-in. scarification. As with the heater-planers, production rates vary with the equipment used, the thermal properties of the asphaltic concrete being scarified, the pavement temperature prior to heating, the depth of scarification desired, and restrictions imposed by auxiliary operations, including addition of an asphalt softening agent or paving mixture. A heater-scarifying unit is shown in Figure 7.

HOT-MILLING

Hot-milling has not been extensively used in the United States. The process is limited to asphalt-surfaced roadways and is performed for the same reasons as given in the section on cold-milling.

The hot-milling machine manufactured by Wirtgen has been used in the eastern United States. The Millars Mark II Road Razer has been used in England. Table 5 lists equipment features, cost information, and fuel consumption information where available. Fuel consumption is on the order of 10,000 Btu/yd² (12 6000 kJ/m²) for these types of devices. Costs are on the order of \$0.80 to

TABLE 4

EXAMPLES OF SURFACE RECYCLING—HEATER-SCARIFIERS

Manufacturer	Equipment Features	Costs		Fuel				Comments
		\$/yd²	Includes	Type	Quantity gal/yd²	BTU /yd²	Includes	
Asphalt Equipment, Inc.	heats and scarifies	0.15-0.28	equipment rental, fuel and labor to heat and scarify	propane				fire horizontally, 3/4-inch scarification
Cutler "Metro" Repaver	heats, scarifies, and can add new mix and/or additive in one operation	0.60	equipment rental	propane diesel	0.09 0.015	8,200 2,100	heating power unit	indirect heating, 1,000 sq yds per hr, 3/4-inch scarification
Cutler "Jumbo" Repaver	heats, scarifies, and can add new mix and/or additive in one operation			propane diesel				indirect heating, 3/4-inch scarification
Jim Jackson Heater-Scarifier	heats, scarifies, and relays scarified mix	0.15-0.30	equipment rental, fuel and labor to heat and scarify	propane	0.08	7,500	heating	direct heating, 2,000 sq yds per hr, 3/4-inch scarification
Payne Heater Scarifier	heats and scarifies	0.18	heat and scarify	propane diesel	0.09 0.06	8,500 8,000	heating, power unit	1,000 sq yds per hr, 3/4-inch scarification

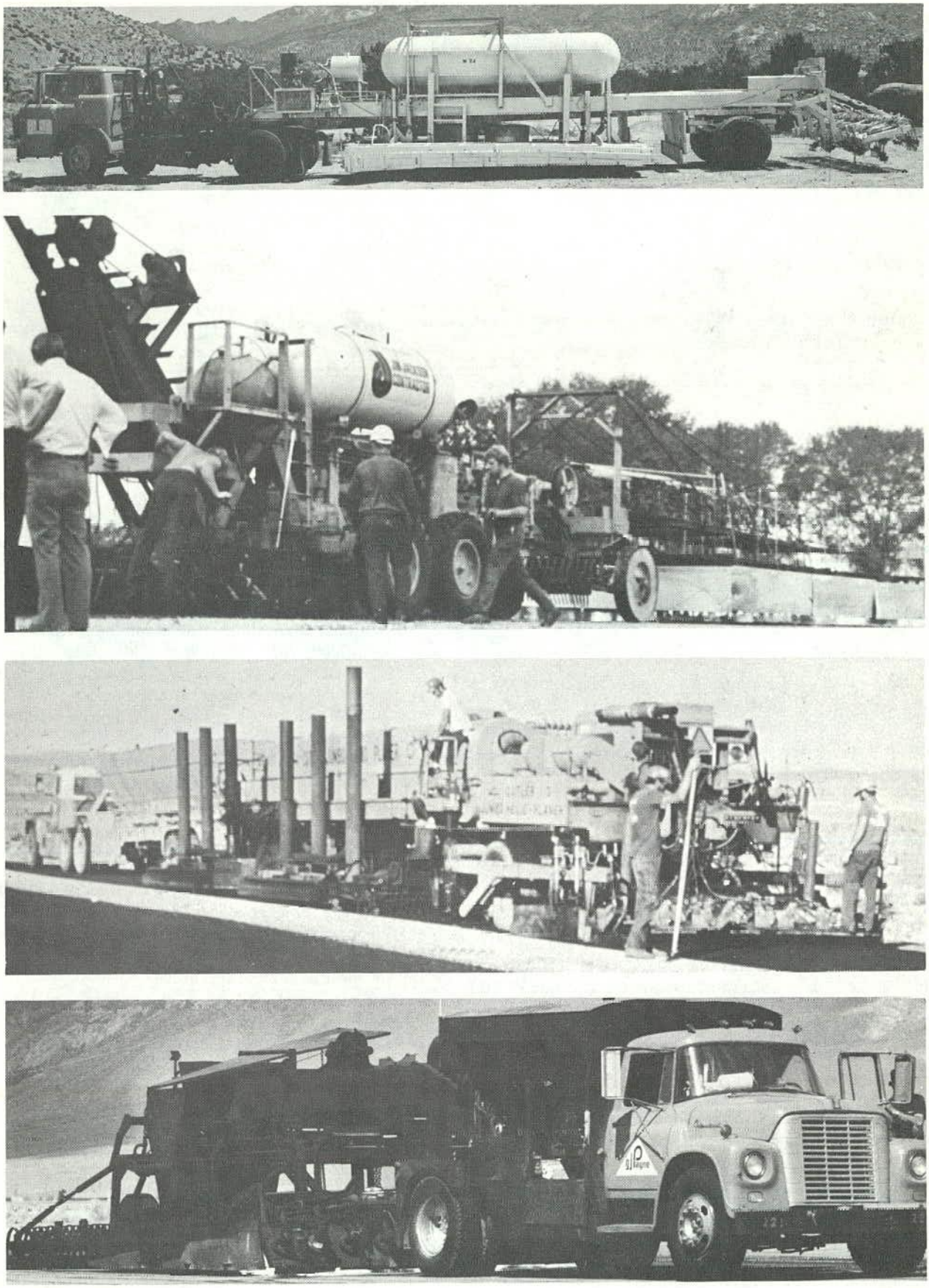


Figure 7. Heater-scarifiers.

TABLE 5

EXAMPLES OF SURFACE RECYCLING EQUIPMENT—HOT-MILLING

Manufacturer	Equipment Features	Costs		Fuel				Comments
		$/yd²	Includes	Type	Quantity gal/yd²	BTU /yd²	Includes	
Millars Mark II Road Razer	heats, planes, and elevates	Not Available		LPG diesel	0.05 0.025	4,600 3,500	heating, power unit	rotary cutter, 1.5 inches removal
Wirtgen SF800/1000	heats and planes			LPG				rotary cutter, small unit
Wirtgen SFM2100B	heats and planes			LPG	0.1	9,000	heating	rotary cutter, 1,000 sq yds per hr, 2.4 inch max. depth

$1.00/yd² ($0.96 to $1.20/m²) for 1-in. (25-mm) removal. These costs include equipment rental, labor, material, and clean-up. Production rates vary with the equipment used, the thermal properties and abrasion resistance of the asphaltic concrete being milled, the pavement temperature prior to heating, and the depth of pavement removal. Existing hot-milling machines are shown in Figure 8. It should be noted that the Wirtgen SF800/1000 is a relatively small unit.

COLD-PLANING

Cold-planing operations are commonly performed in the summer on asphalt-surfaced roadways. The primary purposes of cold-planing are to remove corrugations and other stability failures, to reduce the amount of rutting, and to remove improperly designed or constructed chip seals or slurry seals. The appearance and performance of cold-planing is not as satisfactory in most cases as the heater-planer technique.

Equipment normally used for cold-planing by city and county governments is a motor grader with hardened steel blades. The operation is normally considered to be maintenance, and the removed material is often reused.

The Gurries Company is developing a pavement planer 6.5 ft (2.0 m) wide that is capable of removing 1.5 to 2.0 in. (38 to 50 mm) of asphaltic concrete at a rate of 50 ft (15 m) per minute. This planer removes pavement by use of the vibratory beam concept. A hydraulic system is used to power oscillators that resonate one end of a beam. The beam transmits the vibration to its other end, which impacts a cutting edge. The cutting edge is then used to impact the pavement. The new pavement surface can be expected to have improved skid resistance.

COLD-MILLING

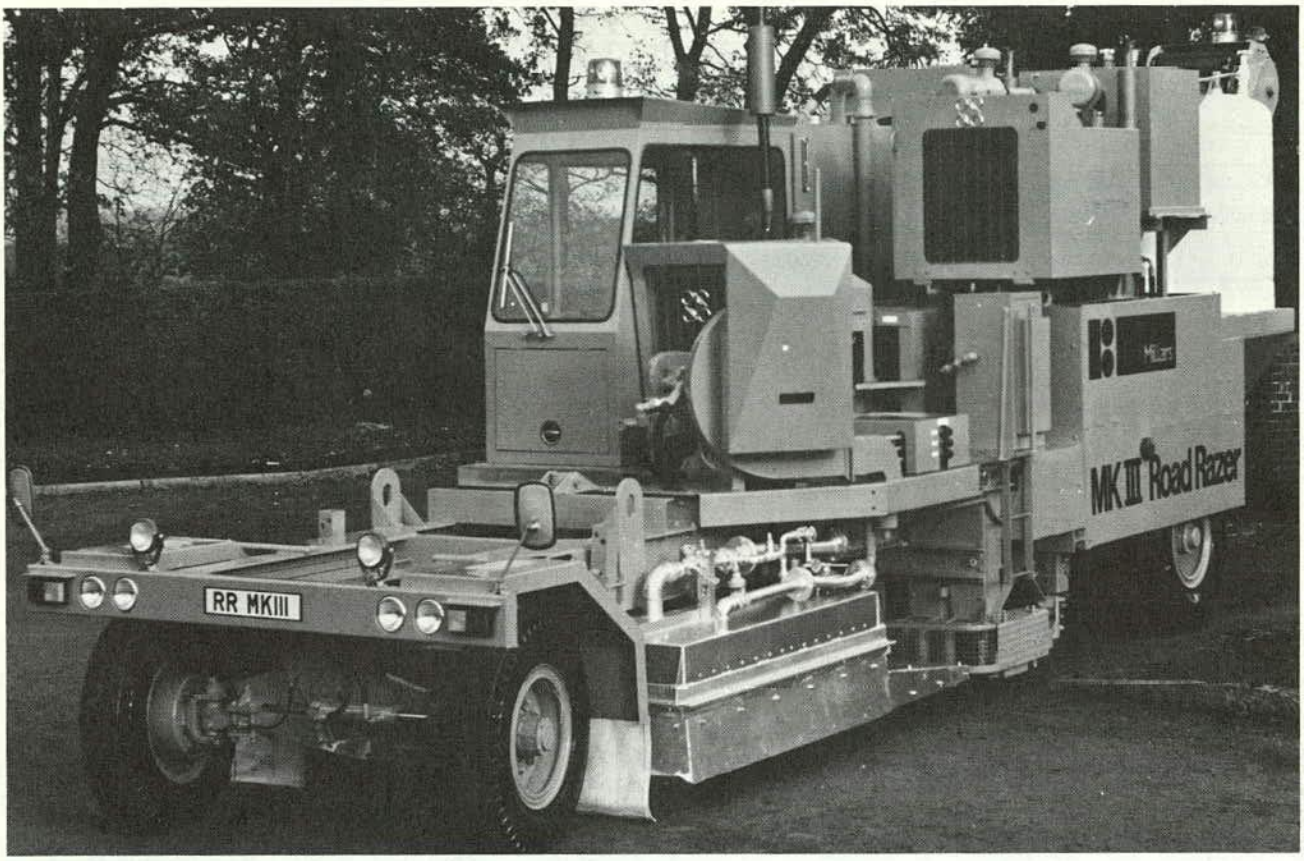
Cold-milling has been performed on both asphalt-surfaced and portland cement concrete-surfaced roadways. The major purpose of cold-milling is removal of surface deterioration; however, the millings could be used for unstabilized base courses or stabilized base or surface courses. The millings could be treated either in place or in a central plant.

The types of pavement distress that could be treated by cold-milling include rutting, raveling, flushing, and corrugations of asphalt-surfaced pavements and rutting, raveling, scaling, faulting, and spalling of portland cement concrete-surfaced pavements. The success of cold-milling depends on the nature and extent of the distress, among other factors.

Additional applications of cold-milling include repairing a rough-riding road, improving skid resistance, and preparing an asphaltic concrete or portland cement concrete surface to receive an overlay. Automated grade control features on many cold-milling machines afford the opportunity to improve ride.

Most milling operations improve the surface texture of the roadway and crush the exposed surface of the aggregate. Both the improved surface texture (macrotexture) and the crushed aggregate (microtexture) promote skid resistance. The improvement in skid resistance may, however, be temporary if the aggregate is polish susceptible. The improved pavement surface texture will also increase the bond or shear strength between the old surface and a new overlay. This bond strength is particularly important for portland cement concrete overlays such as those used on bridge decks.

Most of the cold-milling machines now used have been developed in the last five years. CMI, Barco, and Barber-Greene presently manufacture the largest of these machines, which are capable of milling to a 5-in. (130-mm) depth at 50 ft per minute (0.25 m/s). The BJD miniplaner is a small, maneuverable machine capable of planing near manholes, drainage structures, etc. The Payne 60-in. Pavement Planer and the BJD Miniplaner often work in tandem. Table 6 lists equipment features, cost information, and fuel consumption information where available. Costs for milling and elevating the cut material are on the order of $0.35 to $1.00/yd² ($0.42 to $1.20/m²) for 1-in. (25-mm) removal. Fuel consumption is on the order of 600 to 2,500 Btu/yd² (800 to 3 200 kJ/m²) for 1-in. removal. Production rates may be as



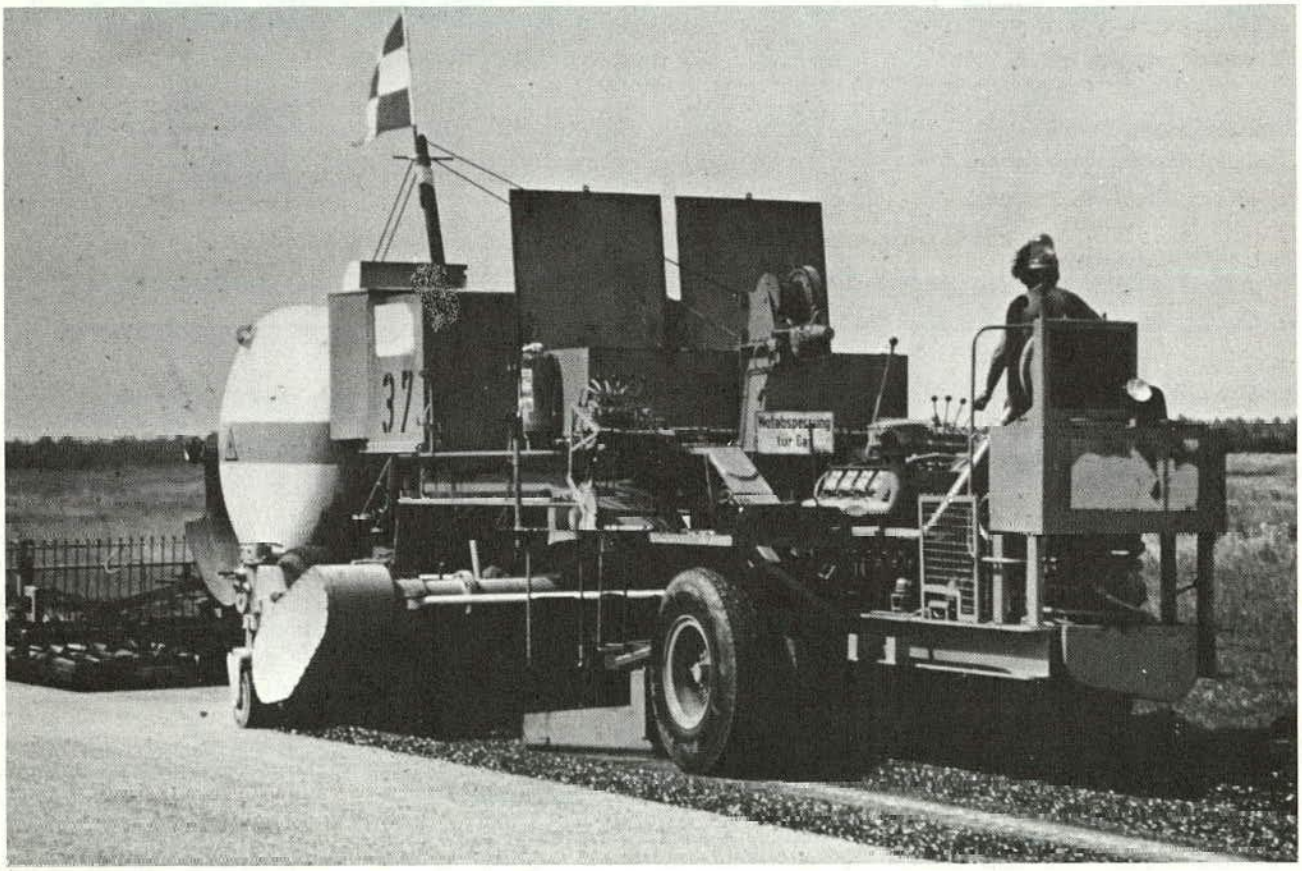


Figure 8. Hot-milling units.

TABLE 6

EXAMPLES OF SURFACE RECYCLING EQUIPMENT—COLD-MILLING

		Costs		Fuel				
Manufacturer	Equipment Features	$/yd^2	Includes	Type	Quantity gal/yd^2	BTU /yd^2	Includes	Comments
Barber-Greene	planes and elevates	0.20-1.00	milling and elevation of material	diesel	.004	600	milling power unit	variable cutting widths
Barco Mfg. Co.	planes and elevates	0.30-1.00	milling and elevation of material	diesel	0.007	1,000	milling power unit	variable cutting widths, 2,000 sq yds per hr, 1-in. removal
BJD Miniplaner	planes			gasoline				12-in. cutting width
CMI Auto-grade Roto-Mill	planes and elevates	0.30-1.00	milling and elevation of material	diesel	0.007	1,000	milling power unit	cutting widths to 150 in., 2,000 sq yds per hr, 1-in. removal
Cutler Eager Beaver	planes							mill to 2-in. depth at 12 to 18 ft per minute
Galion RP-30	planes	0.05	bits and fuel					31-in. cutting width
Payne Pavement Planer	planes	0.35-0.55	milling cleaning, hauling and traffic control to 1-in. depth	diesel	0.015	2,200 to 2,500		60-in. cutting width, 250-300 sq yds per hr, 1-in. removal
Reconeco	planes and elevates			diesel				78-in. cutting width
Sakai	planes			diesel				73-in. cutting width

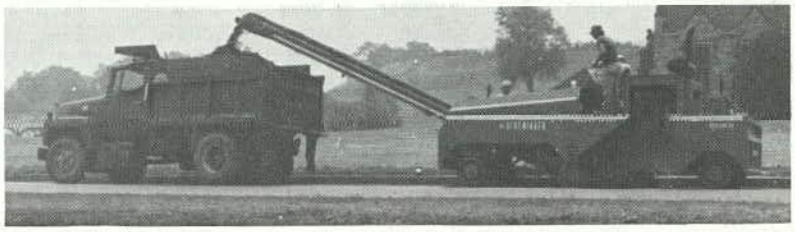
high as 300 tons per hour (270 Mg/h) but vary considerably depending on the equipment utilized, the abrasion resistance of the material being removed, the depth of pavement removal, and the traffic interference. Cold-milling machines are shown in Figure 9.

COMPARISON OF ALTERNATIVES

The New York State Department of Transportation monitored the removal of 1.5 in. (38 mm) of asphaltic concrete by three different methods—heater-planing, hot-milling, and cold-milling (*12*). Items evaluated included air and noise pollution, depth of heat penetration, physical properties of the material both before and after each process, skid resistance of the planed or milled surface, production rate, precision of planing or milling depth, and bond between the new overlay and the milled or planed surface.

All three methods met state standards for air and noise quality in residential areas. Both particulate and hydrocarbon emissions were monitored. Results are given in Tables 7 and 8.

The hot-milling and cold-milling machines were capable of removing material to a depth of 1.5 in. (38 mm) in a single pass. The average removal depth of the heater-planer was ⅜ in. (9.5 mm). The hot-milling machine required the addition of a grader to windrow the milled material, an autoloader to place the material in trucks, and occasionally a front-end loader. The cold-milling operation was performed with two milling machines supplemented by a front-end loader to remove material. The heater-planer unit was self-propelled; however, two identical, independent machines were used on the job. The production capacity, cost, and fuel consumption for the equipment to remove 1.5 in. of asphaltic concrete are given in Table 9.



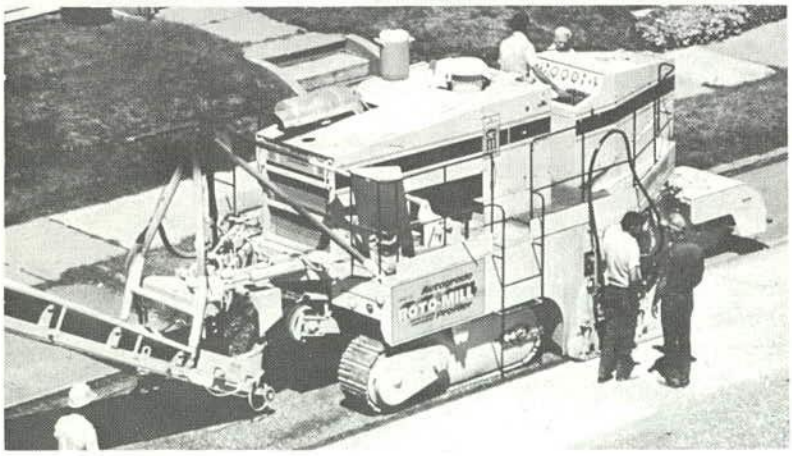


Figure 9. Cold-milling units.

TABLE 7

AIR POLLUTION MEASUREMENTS OF SURFACE RECYCLING EQUIPMENT

Process	Particulates, mg/m^3*	Charcoal Sampler Hydrocarbons, mg/l^3*
Control	85 to 320	0.07
Heater-Planer	1,280 to 2,430	0.04 to 0.48
Hot Miller	1,950 to 2,950	0.10 to 0.90
Cold Miller 303**	23,560 to 152,000	0.20 to 0.48
Cold Miller 304**	60,780 to 450,000	0.22 to 0.46

*Readings made within 5 feet of each machine.
**Both millers, differing only in spray bar capacity, were used in both cold-milling test areas.

(After Nittinger)

TABLE 8

HYDROCARBON SAMPLING BY INFRARED ANALYZER—SURFACE RECYCLING EQUIPMENT

Process and Probe Location	Approximate Concentration, ppm*		
	N**	$\bar{x}$	S
HEATER-PLANER			
In flame area, unprotected	13	37.1	3.3
In flame area, wrapped in asbestos	21	28.8	58.3
About 15 feet from machine	58	2.7	2.7
HOT MILLER			
Attached to front of machine, open-flame burner on slightly	116	26.8	30.3
Attached to front of machine, infrared burner on full	23	86.1	60.0
5 feet ahead of machine, infrared burner off	24	0.0	0.0
5 feet ahead of machine, infrared burner on	115	16.8	12.2
COLD MILLER			
No hydrocarbons detected at any distance			

*Background readings before milling or planing for control purposes found no detectable concentrations of gaseous hydrocarbons; maximum industrial standard allowable is 200 ppm.

**N=number of samples, $\bar{x}$=mean, s=standard deviation.

TABLE 9

NEW YORK SURFACE RECYCLING PROJECT RESULTS *

Type of Equipment	Cost $/yd^2	Fuel Btu's/yd^2	Production per machine - sq yds per day
Heater-Planer	1.20	64,000	1,794
Hot-Miller	1.30	7,300**	7,124
Cold-Miller	1.50		2,254

*Figures shown are for 1.5-inch removal

**Does not include auxiliary equipment

(After Nittinger)

CHAPTER FOUR

IN-PLACE SURFACE AND BASE RECYCLING

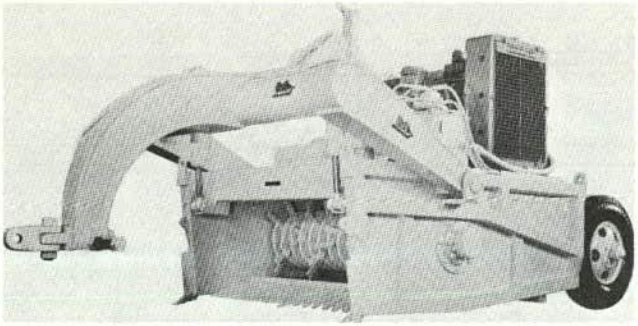
In-place recycling of old asphaltic concrete and portland cement concrete pavement is not a new concept. Almost every state has used conventional construction equipment such as bulldozers, vibratory compactors, rollers, etc., to crush old pavement and combine it with a portion of the existing base or subbase to form a reconstituted structural layer. Development of pulverizing equipment and processing techniques using traveling hammer-mills for recycling asphaltic concrete is among the more important recent refinements of in-place recycling. Figure 10 shows typical in-place recycling equipment.

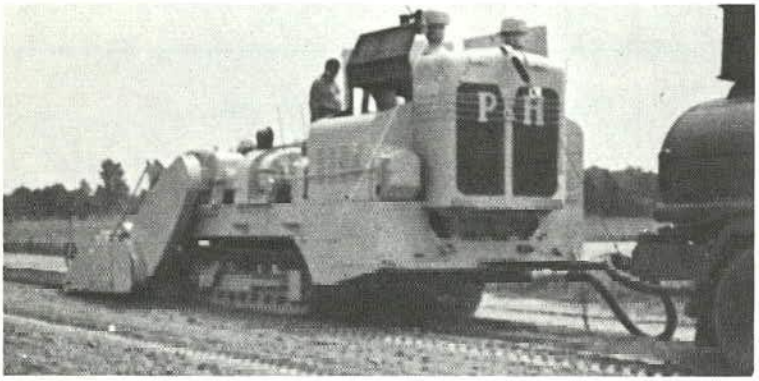
The various alternatives for in-place pavement recycling with no additional heat are shown in Figure 11. Stabilizers such as lime, cement, asphalt, and other chemicals have been used in these processes. Use of cement as a stabilizer for recycled bases and surfaces dates to 1942 (*13*). Use of asphalt with recycled material probably dates to the early 1940s, although the most recent work indicates 1966 (*14*). States that have performed in-place recycling of the type described include Arkansas, California, Florida, Illinois, Indiana, Kansas, Kentucky, Louisiana, Maine, Michigan, Nebraska, Nevada, New Jersey, New York, Pennsylvania, Tennessee, Texas, and Washington. Probably all states have recycled existing bases together with their surfaces without the addition of a stabilizer.

As shown in Figure 11, two basic approaches can be used for in-place recycling, depending on the thickness of the pavement to be treated and the thickness of the asphaltic concrete surface. If the asphaltic concrete surface is about 2 in. (50 mm) or less thick, pulverization equipment can be used without preliminary ripping and breaking. For asphaltic concrete surfaces thicker than about 2 in., motor graders with scarifiers or dozers with ripper teeth are usually used for the initial breakup. Heavy equipment (dozers, rollers, compactors, etc.) can be used if additional breakdown is required prior to pulverization.

A major advantage of in-place recycling is the ability to significantly improve the load-carrying ability of the pavement without changes in the horizontal and vertical geometry of the roadway. Other advantages include the ability to treat almost all types of pavement distress in asphalt-surfaced roadways, to reduce or eliminate reflection cracking, to reduce frost susceptibility of the recycled material, and to improve skid resistance and the ride quality of the roadway (Table 2).

Among the disadvantages are that quality control is not as good as that of central-plant operations, pulverization can not be easily performed on portland cement concrete-surfaced roadways, and cost and traffic disruption may be high.





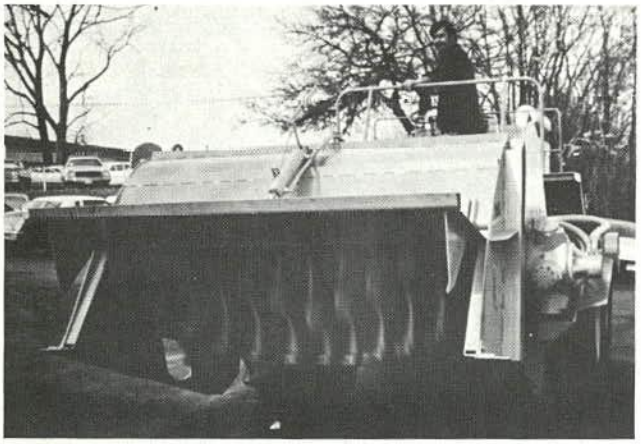


Figure 10. In-place recycling equipment.

MAINTENANCE ACTIVITIES

Surfaces, bases, subbases, and subgrades are commonly removed and replaced by maintenance forces where localized failures occur in the pavement. Certain of these materials can be recycled; thus, the maintenance forces must make a decision. The material may be removed and (a) replaced with a better quality material; (b) replaced with a material that has been stabilized with lime, cement, or asphalt; or (c) the in-place material may be recycled. Cement is often used as a stabilizer for maintenance repairs of bases and subbases. The quantity of cement varies, but about one-half sack per sq yd (25 kg/m^2) for a 6-in. (150-mm) depth is common. The advantage of this type of repair is that in-place materials can be used, thus reducing transportation, handling, and aggregate costs.

FLORIDA EXPERIENCE

Reworking of bases on projects other than "spot" maintenance has also been practiced. One such operation was performed in Florida. The contractor removed the existing base, a 10-in. (250-mm) thick layer of lime rock, and stockpiled it. The subgrade was reworked and sand was hauled in as a subbase. The old, untreated base was put back in place, mixed with the sand, and compacted. This recycled base was then covered with two 5.5-in. (140-mm) layers of new lime rock. The surface was then primed and 3 in. (75 mm) of hot-mix placed (*15*).

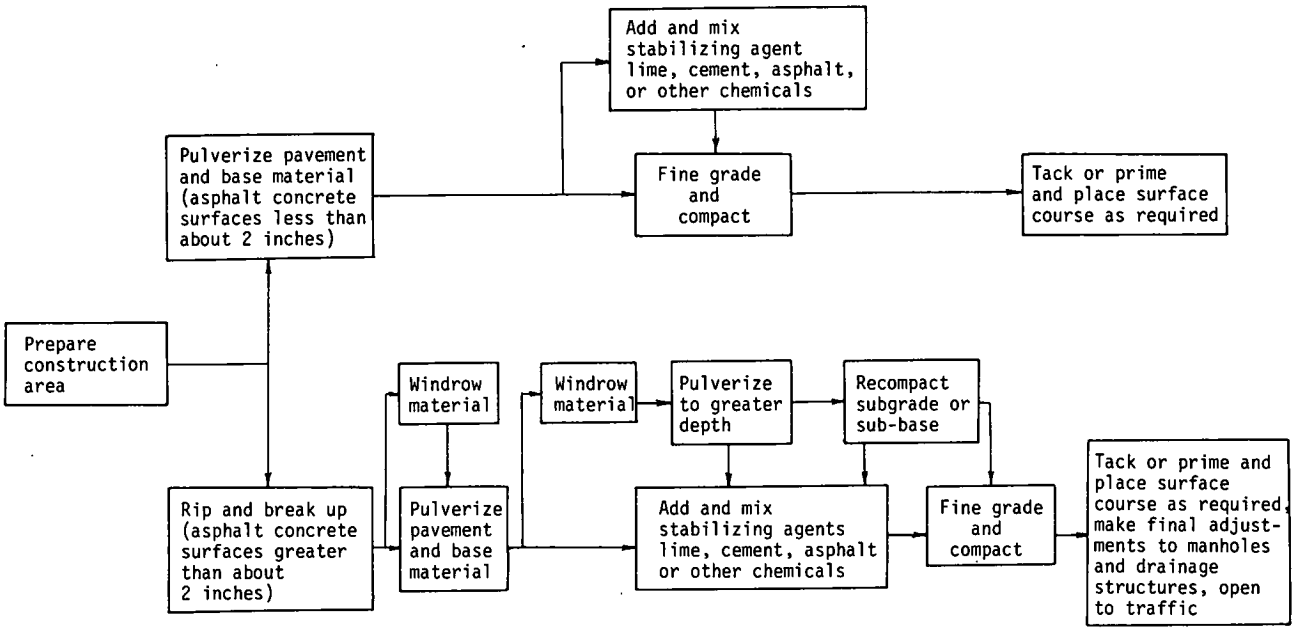


Figure 11. In-place surface and base recycling alternatives.

MICHIGAN EXPERIENCE

Untreated bases may be stabilized in-place by the addition of an agent such as asphalt emulsion. The Michigan Department of State Highways and Transportation has stabilized existing untreated shoulder material with emulsion. One project involved a 2,400-ft (730-m) section of U.S. Highway 131. The existing material was removed to a depth of 4 in. (100 mm) and spread evenly over the adjacent lane. Two percent emulsion was added. Mixing of the emulsion and the aggregate was accomplished by alternating asphalt application and blade mixing. After each application of emulsion, the material was mixed and the top 1 in. (25 mm) was bladed off and windrowed. This process was repeated until all the aggregate was treated and windrowed. The surface of the subbase was primed and the treated materials replaced. Compaction was performed using rubber-tired and steel-wheel rollers. The emulsion-treated base was primed and 4.5 in. (110 mm) of asphaltic concrete surface was placed. Performance of this recycled base has been good (*14*).

Michigan has used a wide variety of stabilizers for in-place shoulder stabilization on an experimental basis. These stabilizers include tars, cutbacks, asphalt emulsions, and asphalt cements. The most common stabilizers used in 1975 and 1976 were asphalt emulsions and soft asphalt cements. When asphalt cement is used as a stabilizer, the hot asphalt is sprayed on the pulverized asphaltic concrete surface course and granular base. A suitable mixture is obtained and adequate compaction can be obtained.

The main lanes of Interstate Highway 75 were recycled in Michigan in Summer of 1977 (*16*). The old 4.5-in. (110-mm) bituminous surface course was pulverized in two steps. The first cut, made with a CMI Rotomill, pulverized the top 2.5 in. (60 mm) of material and placed it in a windrow alongside the roadway. A second cut, made with a Pettibone 660 Hammermill, crushed the remaining 2 in. (50 mm) of bituminous concrete. After crushing, the material was bladed back to a smooth, level cross-section. The crushed material was well graded and contained only a few pieces larger than the 2-in. specified size.

The project was started using a 120- to 150-penetration grade asphalt heated to 335 F (168 C). After some mixing difficulties, a 200- to 250-penetration asphalt was used at a temperature of 370 F (188 C). The asphalt was introduced into the crushed material with a single-pass P and H stabilizer. The pulverized material was not heated prior to adding the asphalt cement.

Immediately after mixing the asphalt, compaction operations were initiated. Initially, the rubber-tired roller operated directly behind the P and H stabilizer. After initial compaction, the surface of this base course layer was graded to the desired shape and compacted with the vibratory roller. Bituminous concrete leveling and wearing courses were applied to complete the construction.

NEVADA EXPERIENCE

Nevada has recycled pavements in place since 1969 [see Table 10 (*17*)]. Portland cement stabilization of pulverized surface and base course has been popular. Each of the following projects (see also Tables 10 and 11) had a 2.5-in. (60-mm) thick asphaltic concrete surface except for Contract 1405, which had a 2-in. (50-mm) thick surface. Pulverization and stabilization was performed to a depth of 8 in. (200 mm). The amount of cement used on the various jobs was:

TABLE 10

NEVADA CEMENT-STABILIZATION PROJECTS

PROJECT	Contract Number	Date of Award	Sq Yd of CTB	Scarification and Pulverization Per Mile	Processing Per Sq Yd	Cement Per Ton	Curing Seal Per Ton	Blotter Sand Per Ton	Cost Per Sq Yd
US 395 from 5.06 miles so. to so. city limits of Gardnerville (5.06 miles)	1332	9/25/69	152,292	$4,000.00	$0.38	$18.40	$57.00	$4.00	$1.00
US 93 between 9.1 miles and 19.1 miles no. of jct. with US 40 in Wells (10 miles)	1348	4/16/70	205,340	$3,000.00	$0.46	$20.83	$45.00	$5.00	$1.04
US 93 between 19.1 miles and 29.1 miles no. of jct. with US 40 in Wells (10.0 miles)	1391	5/7/71	205,340	$8,000.00	$0.30	$17.36	$42.00	$5.00	$1.10
SR 80 and 17 from jct. SR 80 and 17 so. of Silver City to 1 mile no. of jct. SR 80 and 17 in Virginia City (3.0 miles)	1405	7/29/71	42,240	$5,600.00	$0.355	$20.83	$84.50	$10.00	$1.45
US 93 between 29.1 miles and 38.0 miles no. of jct. with US 40 in Wells (8.93 miles)	1436	4/27/72	183,280	$8,900.00	$0.25	$19.05	$78.50	$5.70	$1.06
US 93 between 9.1 miles no. and Jct. with U.S. 40 in Wells (9.1 miles)	1524	6/12/75	186,150	$9,000.00	$0.44	$50.00	$113.00	$20.00	$1.38

(After Marsh)

Contract No.	Cement Added (% by Weight)
1332	3
1348	3
1391	3
1405	4.5
1436	3
1524	1.5

Averaging the latest four contracts results in a scarifying and pulverization cost of approximately $0.45/yd² ($0.54/m²). The total cost, with 8 in. (200 mm) of cement stabilization, ranged from $1.38/yd² ($1.65/m²) for 1.5 percent cement to $2.24/yd² ($2.68/m²) for 4.5 percent cement. Investigations of the bid prices by the Nevada Department of Highways indicated that on five of the six contracts no dramatic cost savings were experienced by pulverizing and cement-treating the existing surface and base material. It would have been more economical to increase the depth of bituminous overlay. However, frost susceptibility of the pavement section was reduced, and maintenance costs may also have been reduced.

TABLE 11

RECYCLING COSTS IN NEVADA *

Contract Number	Year	Processing $/yd²	Processing $/m²	Adjusted Total Cost $/yd²	Adjusted Total Cost $/m²
1332**	1969	0.65	0.78	1.70	2.03
1348	1970	0.75	0.90	1.69	2.02
1391	1971	0.46	0.55	1.70	2.03
1405	1971	0.55	0.66	2.24	2.68
1436	1972	0.37	0.44	1.56	1.87
1524	1975	0.44	0.53	1.38	1.65

*Costs were obtained by adjusting the quoted prices to reflect 1975 cost increases.

**This project was felt to be underbid (17).

TEXAS EXPERIENCE

District 8 personnel of the Texas State Department of Highways and Public Transportation completed an in-place recycling project in October 1975. Approximately 1,500 ft (460 m) of U.S. Highway 277 south of Abilene, Tex., was recycled in-place. The highway consisted of a limestone base, a two- or three-course surface treatment, 2 in. (50 mm) of asphaltic concrete overlay, a seal coat, another hot-mix asphaltic concrete overlay, and an additional seal coat. An average asphalt mixture thickness of 4.5 in. (110 mm) existed on this facility.

A bulldozer with a ripper was used to break up the asphaltic pavement. The tracks of the dozer were used to reduce the pavement chunks to a maximum dimension of 14 in. (360 mm). After ripping, the material was bladed into a windrow containing 3 ft³ per linear ft (0.3 m³/m). Water and a recycling modifier were added to the windrow to control dust and soften the mixture. A Pettibone P-500 traveling hammer-mill was used to pulverize the material. The hammer-mill, driven by a power unit, contained 24

rotating hammers, each weighing 60 lb (27 kg). The hammer-mill was pulled by a front-end loader. Maximum production for this equipment is about 200 tons (180 Mg) per hour. Two passes of the hammer-mill were used to pulverize the pavement. After pulverization, the material was bladed to the side of the roadway, and the next windrow of broken pavement was prepared for pulverization. After an entire lane was pulverized, a conventional in-place asphalt stabilization process was used. Asphalt emulsion, blended with water on a one-to-one basis, was used for this operation. A Pettibone SM-750 in-place stabilization machine was used to mix the recycled material and emulsion. This machine can mix to a depth of 16 in. (400 mm). Following this operation, the stabilized material was laid with a blade and compacted with a self-propelled steel-wheel vibratory roller. A surface course of hot-mixed, cold-laid material was laid over the recycled material to provide a smooth surface (*18*). The costs incurred on this project are given in Table 12.

TABLE 12

RECYCLING PROJECT COST (TEXAS)

Item	Total Cost	Cost yd^2	Cost m^2
Salary and labor	$ 4,687.48	$0.50	$0.60
Equipment rental*	10,014.75	1.08	2.15
Stock issues	8,187.40	0.88	1.05
Traffic controls**	4,760.90	0.51	0.61
Engineering	917.00	0.10	0.12
Total	$28,567.53	$3.07	$3.67

*Special equipment rental is included in the total cost as follows:

Pettibone P-599 pulverizer	$3,600 per month
Pettibone C-205 vibratory roller	$1,500 per month
Pettibone SM-750 Speedmixer	$2,000 per month

**This item includes all barricades, warning signs, temporary and final traffic control markings for the project.

(After Lindley)

MIDWEST ASPHALT PAVING CORPORATION

The Midwest Asphalt Paving Corporation, operating in and near the Detroit area, has performed a number of in-place stabilization contracts using modified Koehring and BROS equipment (*19*). Costs for performing these operations vary, depending on thickness to be stabilized, thickness of asphaltic concrete surfacings, type of base material, traffic control requirements, size of the job, material costs, labor costs, equipment availability, and other factors.

For estimating purposes, Midwest used a cost of $2.00/$yd^2$ ($2.40/$m^2$) for gravel-surfaced roads in 1976. This cost includes a two-course surface treatment at $0.65/$yd^2$ ($0.78/$m^2$) and any one of the following pulverization and stabilization operations:

1. 4-in. (100-mm) pulverization and stabilization with 2 gal/yd^2 (9L/m^2) of 200- to 250-penetration asphalt cement.
2. 6-in. (150-mm) pulverization and stabilization with 28 lb/yd^2 (15 kg/m^2) of hydrated lime.
3. 6-in. pulverization and stabilization with 34 lb/yd^2 (18 kg/m^2) of Type I portland cement [12,000 yd^2 (10 000 m^2) on larger projects].

Asphaltic concrete-surfaced roadways are more difficult to pulverize, thus a charge is added to that required for gravel roads as follows:

1. 2-in. (50-mm) asphaltic concrete surface—$0.45/$yd^2$ ($0.54/$m^2$) additional.
2. 4-in. (100-mm) asphaltic concrete surface—$0.65/$yd^2$ ($0.78/$m^2$) additional.
3. 6-in. (150-mm) asphaltic concrete surface—$0.85/$yd^2$ ($1.02/$m^2$) additional.
4. Multiple seal-coat surface—no additional cost.

Production obtained by Midwest is approximately 6,000 yd^2 (5 000 m^2) per day. Fuel consumption is approximately 200 gal (760 L) of diesel per day or 4,500 Btu/yd^2 (5 700 kJ/m^2).

Pavements recycled as described have performed satisfactorily under urban traffic.

INDEPENDENT CONSTRUCTION COMPANY

Independent Construction Company of Oakland, Calif., has used a Metradon Model 127 Pulverizer for in-place pavement recycling. The normal construction sequence with this pulverizer consists of (a) ripping the pavement with a tractor equipped with ripper teeth, (b) reducing the pavement chunks from about 24 by 9 in. (600 × 230 mm) to 4 to 6 in. (100 to 150 mm) by use of a drum compactor equipped with cutter pads (this compactor is similar to those used for municipal landfill compaction operations), (c) reducing the pavement chunks further with a segmented wheel roller, (d) pulverizing the material to 1.5-in. (38-mm) maximum size with the Metradon equipment, and (e) stabilizing it using conventional equipment. The Metradon pulverizer is pulled by a bulldozer. As the unit moves forward, the material to be pulverized moves into the scraper and is impacted by 64 blades attached to a shaft, which rotates at 1,250 rpm.

One of the documented jobs by the Metradon was performed in Yolo County, Calif., on a secondary state highway designed for cars and trucks carrying farm equipment and farm products. The asphaltic concrete surface varied in depth from 3 to 9 in. (75 to 230 mm) and had deteriorated severely in some areas. The existing asphaltic concrete pavement was pulverized such that 90 percent passed the 1.5-in. (38.1-mm) sieve. The pulverized pavement was mixed with the clayey subgrade material and 4 percent by weight of lime was added to create a 10-in. (250-mm) compacted, lime-treated base. The resulting lime-stabilized material was overlayed with 2.5 in. (60 mm) of asphaltic concrete about 6 months after the lime stabilization (*20*). The cost to rip, pulverize, add lime, mix, compact the 10-in. section, and add 2.5 in. of asphaltic concrete was $5.35/$yd^2$ ($6.40/$m^2$).

On this same job, if the state had furnished the lime and water but the contractor had hauled and spread these materials, a price of $2.12/yd² ($2.54/m²) would have been quoted. If the state had furnished the lime and water as well as hauling and spreading these materials, a cost of $1.77/yd² ($2.12/m²) would have been quoted (*21*).

BELL AND FLYNN, INC.

Bell and Flynn, Inc. have been recycling old asphaltic pavements into untreated base courses since 1964 by use of the BROS Traveling Hammermill. Both highway and airfields have been recycled; depths have ranged from 2 to 10 in. (50 to 250 mm). A typical sequence of construction is as follows:

1. Cut outboard edges of pavement construction limits with a diamond saw.
2. Scarify and break up the existing pavement.
3. Grade and develop windrows of the broken pavement surface and base (the depth of base course to be included in the pulverization depends on the gradation required and the end use of the material).
4. Perform the primary crushing of the pavement and base.
5. Grade and develop new windrows of crushed material for a second crushing.
6. Perform the secondary crushing of the pavement and base.
7. Remove all crushed material from the work area by grading into outboard windrows.
8. Fine-grade and compact the subbase.
9. Grade the crushed material and place on the subbase as a stabilized base course.
10. Fine-grade and compact the stabilized base course.
11. Apply a tack coat and surface the roadway.

A recent project using the BROS Hammermill has been completed in Maine. This project was undertaken as part of FHWA Demonstration Project 39 on Recycling Asphalt Pavement. The project consisted of recycling 1 mile (1.6 km) of Interstate 95 south of Bangor and 2 miles (3.2 km) of State Route 9 east of Bangor. On I-95, a BROS portable hammermill was used to reconstitute 3 in. (75 mm) of asphaltic concrete, 5 in. (125 mm) of penetration macadam, and 4 in. (100 mm) of crushed-stone base into a base material. This base was then overlayed with 2.5 in. (60 mm) of asphaltic concrete. On SR 9, the existing 1-in. (25-mm) pavement and 3-in. gravel base were pulverized, removed, and relaid as a base on a new alignment. A 1.5-in. (38-mm) overlay of asphaltic concrete was used as the surface course. The I-95 and a portion of the SR 9 projects were completed in the fall of 1975. In the spring of 1976 it was apparent that both sections were not performing satisfactorily. Although the final analysis is not complete, the late fall construction, frost, moisture, and heavy loads probably contributed to the failure (*22*).

State Route 9 was completed in the summer of 1976 with asphalt emulsion used to stabilize a portion of the recycled material. This section, together with the other sections that have been overlayed, will be monitored by the Maine Department of Transportation.

Bid prices for pulverization on this project ranged from $0.25 to $0.40/yd²-in. ($0.12 to $0.19/m²-cm), depending on the thickness of the material to be pulverized.

In 1972, Bell and Flynn, Inc. illustrated that a 15 percent saving could be achieved on a 2-in.-thick (50-mm) asphaltic concrete runway by crushing and mixing the existing surface and base. Costs for the two alternatives are given in Table 13 (*23*).

The resulting unit costs for alternatives A and B were $6.72/yd² ($8.04/m²) and $7.43/yd² ($8.89/m²), respectively.

The city of Lynn, Mass., also found that it could save about 35 percent in costs by recycling the existing asphaltic surface rather than using conventional methods. Comparative costs are given in Table 14 (*24*). Unit costs for the recycled and conventional methods were $4.41/yd² ($5.27/m²) and $6.61/yd² ($7.91/m²), respectively.

PETTIBONE EQUIPMENT

Equipment manufactured by Pettibone was used in Buena Park, Calif., in December 1975. The pulverized 4- to 6-in.-thick (100- to 150-mm) pavement was moved to one side and the existing subgrade was undercut and removed. Upon completion of the subgrade, the pulverized pavement was used as subbase for the new asphaltic pavement. Costs for this project are given in Table 15 (*25*) and include pulverization, grading, compaction, and hauling of surplus material. As a comparison, costs for an equivalent conventional operation with 4 to 6 in. (100 to 150 mm) of all-new material were as follows (*26*):

Roadway excavation	14,500 cy @ $2.85
Aggregate subbase	5,200 cy @ $3.30
Total cost	$58,485
Total cost per yd²	$2.31

The Pettibone Corporation estimates that the cost simply to rip, pulverize, remix, and compact a 4-in.-thick (100-mm) pavement is about $0.54/yd² ($0.65/m²). Independent Construction Company estimates this same operation for a 5-in.-thick (125-mm) pavement to be $0.67/yd² ($0.80/m²) (*21*).

Two projects using Pettibone equipment were completed in 1976 as part of the FHWA Demonstration Project program. Three miles (4.8 km) of County Road M on the Menominee Indian Reservation in Wisconsin were pulverized with the Pettibone P-500. The project consisted of four 1-mile (1.6-km) test sections as follows:

1. A control section consisting of a conventional 2-in. (50-mm) overlay.
2. A section containing a chemical to stabilize the pulverized material and covered with a 2-in. (50-mm) overlay.
3. A section identical to Section 2 except the chemical was not used.

TABLE 13

RUNWAY RECYCLING COST (*23*)

Alternative A: Grinding up old pavement, mixing with base

Item	Quantity	Amount
Unclassified excavation	50 CY	$ 250.00
Subbase (on-site)	600 CY	6,600.00
Stabilized base course prep	32,500 SY	73,125.00
Bituminous tack coat	6,600 gals.	7,260.00
Bituminous concrete	4,300 tons	58,050.00
Runway painting		3,000.00
		$148,285.00

Alternative B: Discarding old pavement, importing fresh aggregate

Item	Quantity	Amount
Unclassified excavation	2,100 CY	$ 8,400.00
Offsite crushed aggregate	4,800 tons	50,400.00
Aggregate base course	32,500 SY	35,750.00
Bituminous prime coat	16,500 gals.	8,250.00
Bituminous concrete	4,300 tons	58,050.00
Runway painting		3,000.00
		$163,850.00

4. A section with a chemical and on asphalt emulsion to stabilize the pulverized material and covered by a 2-in. (50-mm) overlay.

Three sections of a county road in Elkhart County, Ind., have been recycled with a chemical stabilizer. About 2 to 4 in. (50 to 100 mm) of old pavement have been pulverized and stabilized for use as a surface course. Reports documenting these projects are not available at this time.

The FHWA Demonstration Project program is monitoring several 1977 in-place recycling projects. Projects are located in the States of Washington, Texas, Kansas, and Michigan.

COMPARISON OF ALTERNATIVES

In-place recycling of asphaltic concrete less than about 2 to 4 in. (50 to 100 mm) in depth can be accomplished without a great deal of preliminary ripping and materials handling. The recycling of asphaltic concrete greater than about 4 in. in depth requires ripping, some preliminary crushing, and windrowing prior to pulverization.

Data obtained from projects involving the Pettibone or the Independent Construction Company equipment have indicated that the cost to rip, pulverize, remix, and compact is approximately $0.15/yd²-in. ($0.07/m²-cm). Midwest Asphalt Paving Corporation has indicated that costs for ripping; pulverizing; stabilizing with lime, cement, or asphalt; and recompacting are on the order of $0.30 to $0.50/yd²-in. ($0.14 to $0.24/m²-cm). Major equipment maintenance problems have occurred on several projects.

TABLE 14

COST COMPARISON, WYMAN STREET RECLAMATION PROCESS VS. CONVENTIONAL RECONSTRUCTION (*24*)

Item		Recycled (12-in. depth)	Conventional (est.)
Base preparation (7,398 SY)	Bid	$15,000	---
	Labor	---	$9,700
Gravel replacement		---	4,200
Equipment cost, depreciation & fuel		---	9,100
Casting adjustments (manhole, catch basins)		1,200	1,200
Bituminous concrete wearing surface (3 in. thick)		---	12,330
(2 in. thick)		8,220	---
	Total cost	$24,420	$36,530

TABLE 15

RECYCLING COSTS—BUENA PARK, CALIF.

Equipment	Labor Cost	Equipment Cost
P-660 Pulverizer		$3,100 including hammers
P-550 Pulverizer		5,600 " "
D8 dozer		2,800
Model 14 grader		2,400
Water truck		800
Elevating scraper		1,400
C-205 vibratory compactor		1,400
Haul trucks		4,800
950 loader		2,000
Operators	$ 6,140	
Laborers	2,080	
Foreman	1,280	
Teamsters	3,400	
	$12,900	$24,300
	Total cost	$37,200
	Total cost per yd²*	$ 1.47

*4 to 6 in. of recycled pavement

(After "Recycle Your Tax Dollar")

CHAPTER FIVE

CENTRAL-PLANT RECYCLING

Central-plant surface and base recycling has been practiced for a number of years. Pavement and building rubble has been crushed and used as both unstabilized and stabilized base course in Washington, D.C., Los Angeles, Minnesota, and San Francisco. Several of the approaches shown in Figure 12 have never been used on a large scale or only recently have been used on an experimental basis. For example, the recycling of portland cement concrete back into portland cement concrete has only been investigated briefly in the laboratory (*26, 27, 28, 29, 30, 31*) in the United States, and one experimental project was placed in Iowa (*32*). Recycling of asphaltic paving surfaces into asphaltic concrete using central-plant operations had an early history with Warren Brothers in 1915 (*33*), but very little experimentation was conducted from that time until 1974 (*34*).

Processes involving use of additional heat in central plants and asphalt cement as the stabilizer have a tremendous future. It is anticipated that about 10 percent of the asphaltic concrete hot-mix market will be supplied by heated central-plant recycling operations in the next three to five years (*35*). Thus, 30 to 35 million tons (27 to 32 Tg) will be produced from about 200 plants. The plants will either be new plants or existing plants (numbering in excess of 4,700), which will be altered to solve pollution problems that arise when asphalt mixtures are recycled.

Increased interest in central-plant recycling has led to development of new techniques for heating the reused materials (Fig. 12), as well as new concepts for pavement removal and sizing.

Two approaches have been used to size the material prior to recycling in a central plant. The pavement can be reduced in size in-place and then hauled to the central plant, or the pavement can be removed from the site and crushed at the central plant. In-place or on-grade removal and sizing can be performed with equipment normally associated with surface and in-place recycling; specifically, hot- and cold-milling machines, heater-planing equipment, and on-grade pulverizers.

Central-plant sizing can be performed with conventional, fixed, and portable crushing and screening equipment. The pavement is normally ripped and broken up prior to loading in a size suitable to be received by the primary crusher. In some instances, it is economical to use grid rollers and other types of construction equipment to produce a suitably sized material on the roadway prior to hauling to the central plant. Jaw and roll crushers have proven to be satisfactory.

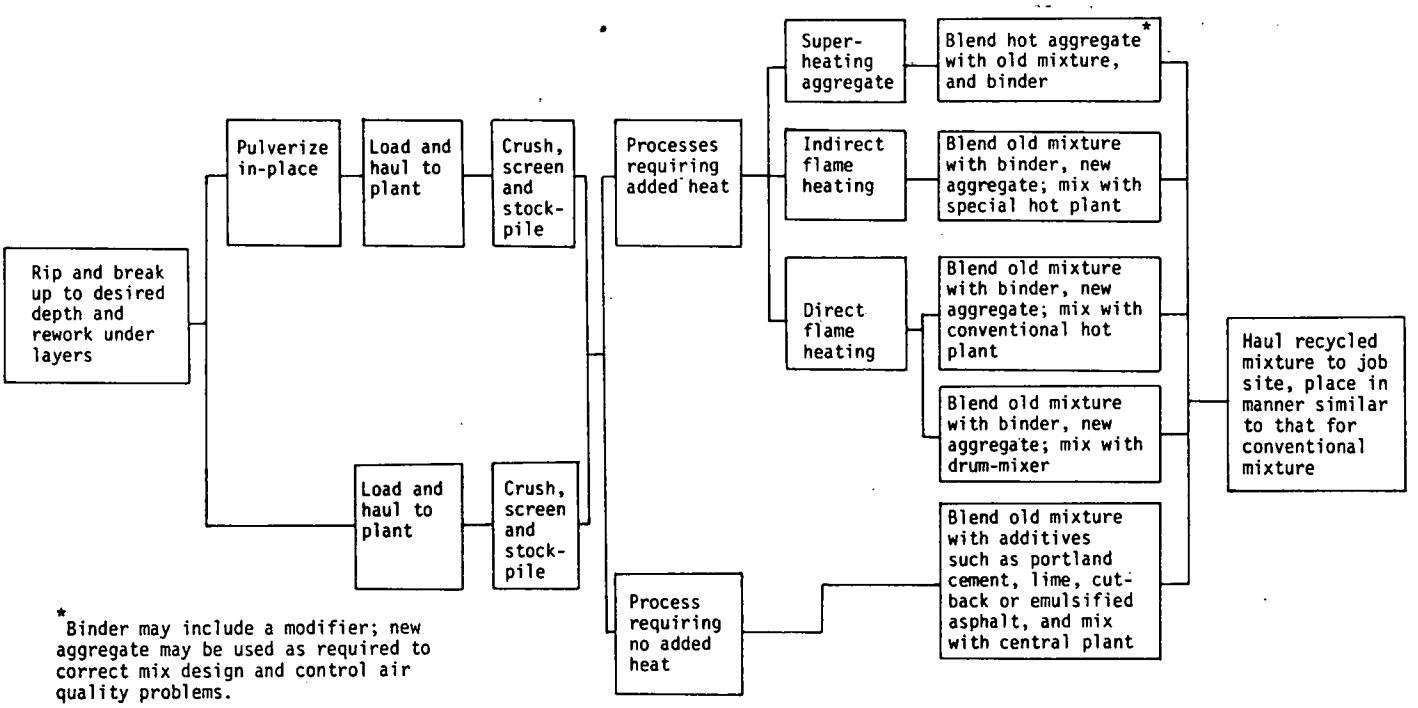


Figure 12. Central-plant recycling techniques.

CENTRAL-PLANT RECYCLING TECHNIQUES

Equipment to centrally hot-process the recycled material is available, and for convenience can be separated into at least three general categorise (Fig. 12):

1. Direct flame heating.
2. Indirect flame heating.
3. Superheated aggregate.

Direct Flame Heating

Direct flame heating is typically performed with a drum mixer wherein all materials are mixed simultaneously in a revolving drum with a flame at one end. The standard drum mixer plant has been used on experimental jobs in Texas and Arizona. Problems with air quality have led to several modifications, such as the addition of heat shields, split feeds, etc.

The heat shield (Fig. 13) and additional cooling air are used to reduce the hot gasses to a temperature below about 800 to 1200 F (425 to 650 C) and thus reduce the amount of blue smoke formation. This type of equipment can successfully recycle mixtures up to about 70 percent recycled asphaltic concrete. It has been used in Arizona, Oregon, Texas, and Utah.

The concept of a drum within a drum has been used in Iowa (Fig. 14). This process is based on a small-diameter drum inserted in the charging end of a conventional drum mix unit. New or virgin aggregate is introduced into the inner drum, where it is superheated to 300 to 500 F (150 to 260 C). Reclaimed materials are introduced into the outer drum through a second changing chute. The reclaimed material and the heated virgin material meet at the discharge point of the inner drum, where heat transfer occurs. This type of equipment can successfully recycle mixtures containing up to about 50 to 60 percent recycled bituminous materials.

Split-feed drum mixers were first used in 1976 (Fig. 15). New aggregate is introduced at the flame end of the drum, where it is superheated to 300 to 500 F (150 to 260 C). At about the midpoint of the drum, the recycled bituminous material is introduced and is heated by the hot gasses as well as by heat transfer from the superheated new aggregate. This type of equipment, which has been used in Minnesota and Oklahoma, can successfully recycle mixtures containing up to about 60 to 70 percent recycled bituminous materials.

Indirect Flame Heating

Indirect flame heating has been performed with special drum mixer exchanger tubes (Fig. 16). These tubes, which transfer the gasses, prevent the mixtures from coming into direct contact with the flame and extremely high temperatures. These plants can recycle up to 100 percent bituminous materials. They have been used in Nevada.

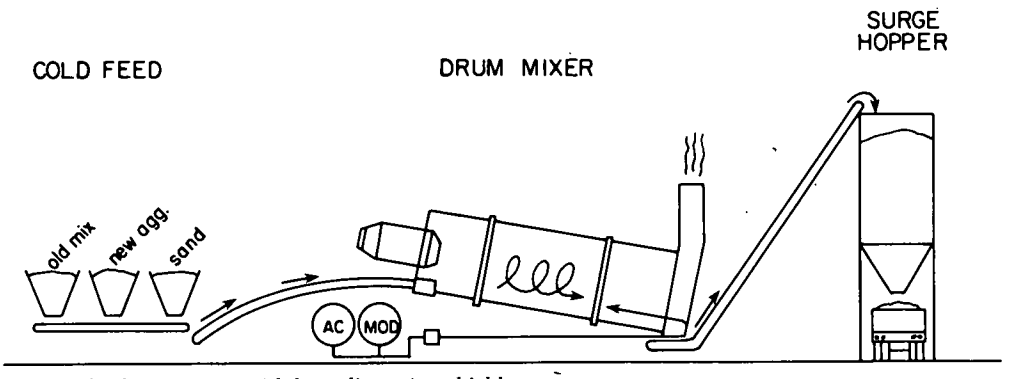


Figure 13. Drum mixer with heat dispersion shield.

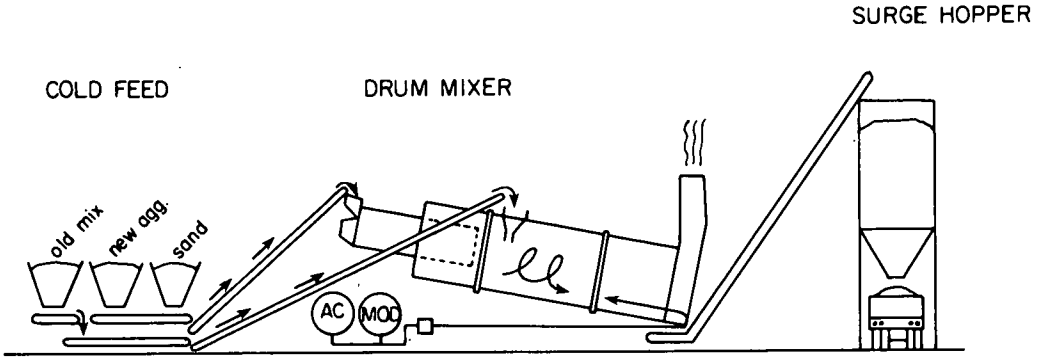


Figure 14. Drum-within-a-drum plant.

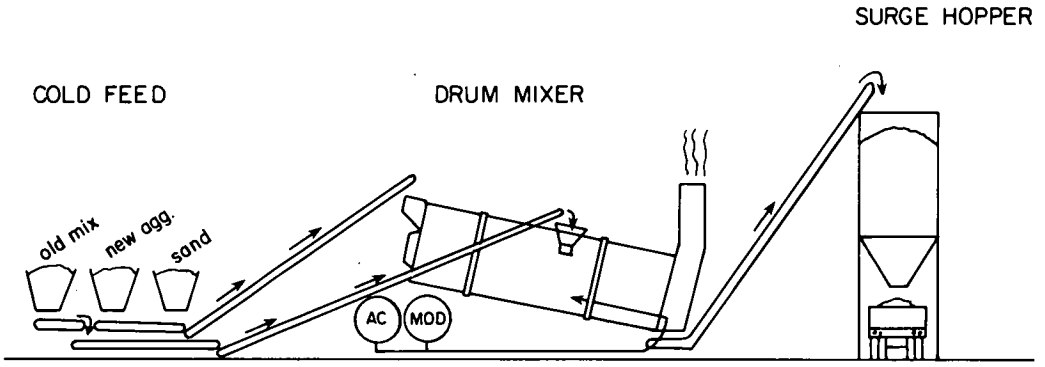


Figure 15. Drum mixer with split feed.

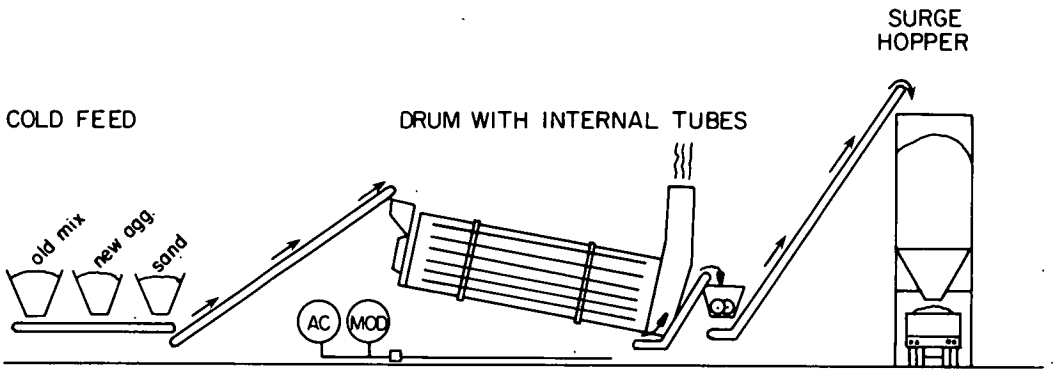


Figure 16. Special drum mixer with heat-exchanger tubes.

Superheated Aggregate

Superheated aggregate can be used to heat recycled bituminous material. As noted, two of the direct flame methods make use of this concept to partially heat the recycled material. Figures 17, 18 and 19 show methods that use superheated new aggregate to heat the recycled mixture. Standard plants can be used for this approach. Figures 17 and 18 illustrate different locations of blending the new aggregate and the recycled bituminous material. The process shown in Figure 17 has been used in Minnesota and Virginia.

Tandem drum mixers can also be used. The first drum can be used to superheat new aggregate. The second drum can then be used either to heat the recycled mixture (Fig. 19) or to mix and heat the new and recycled materials. It is possible to use exhaust gasses from the first drier as a heat source for the second drier unit. The tandem drum concept has been used in Washington.

The central-plant recycling technique utilizing superheated aggregate is limited to about 50 percent recycled bituminous materials.

Without Heat

The final version of central-plant recycling to be discussed is without the addition of heat (Fig. 20). High production rates can be obtained with this type of plant using lime, cement, or asphalt as a binder. This cold central-plant recycling operation can use up to about 100 percent recycled bituminous materials.

Users of Central-Plant Recycling

Contractors and equipment manufacturers that have been actively engaged in recycling using central-plant operations are listed in Appendix A. Figure 21 shows some central-plant recycling equipment. Arizona, Iowa, Minnesota, Nevada, Oregon, Texas, Utah, Virginia, Washington, and Wyoming have been the most active involving central-plant recycling. Most jobs prior to 1978 involving the use of additional heat were limited in scope and can for the most part be called experimental. RMI Systems' prototype plant, with a capacity of about 85 tons per hour (77 Mg/h), has been used on several jobs dating back to 1974. A large version of the RMI Systems plant has been used on a job on I-15 near Las Vegas, Nev. This plant has a capacity of about 200 tons per hour (180 Mg/h). Several experimental and large-scale jobs were performed during the 1976, 1977, and 1978 construction seasons to solve certain equipment-related problems associated with the "hot" central-plant recycling efforts. These projects are located in Arizona, California, Iowa, Minnesota, Oklahoma, Oregon, Texas, Utah, Washington, and Wyoming.

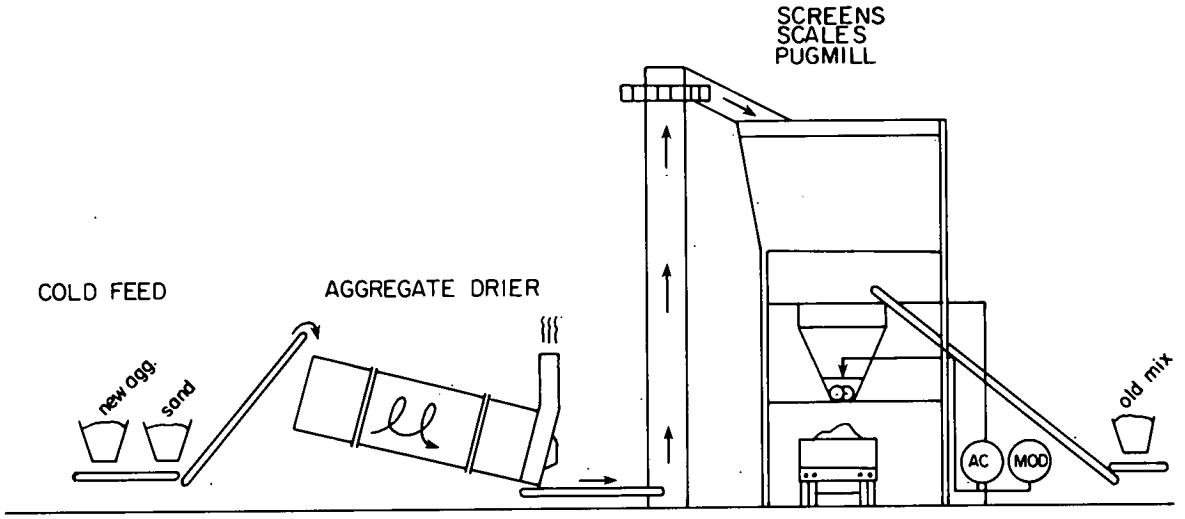


Figure 17. Standard batch plant with old mix added to superheated aggregates at the pug mill.

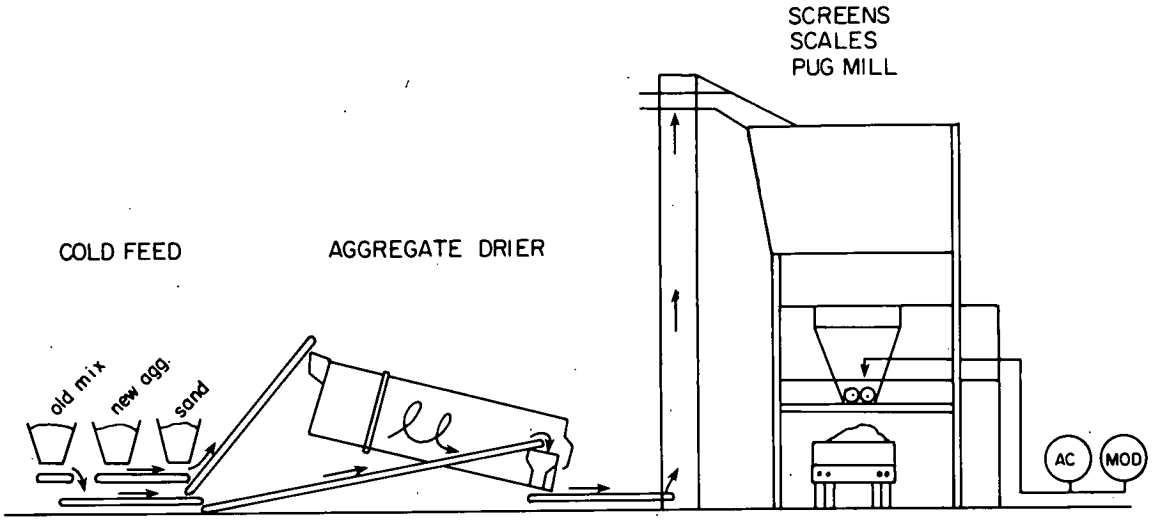


Figure 18. Standard batch plant with old mix added to superheated aggregate at drier discharge.

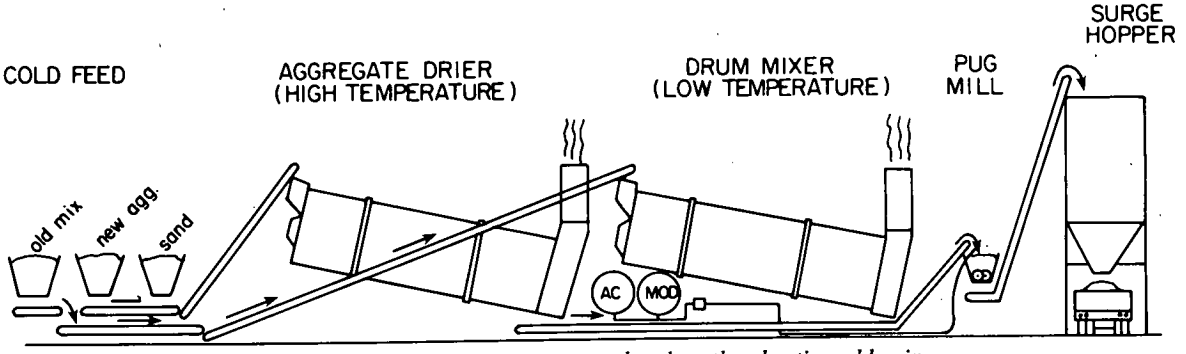


Figure 19. Tandem drum mixers—one heating aggregate only, the other heating old mix, binder.

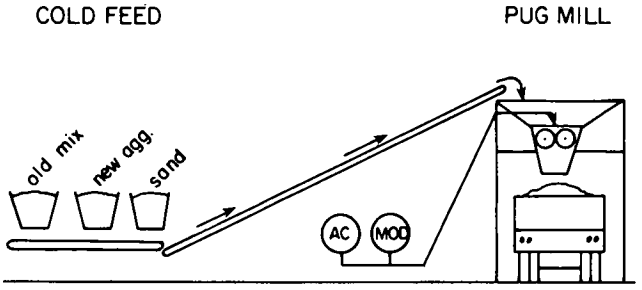


Figure 20. Cold-mix plant.

Advantages and disadvantages of central-plant recycling are given in Table 2.

The following discussion separates central-plant recycling operations into categories based on the type of material recycled: cement-treated, including portland cement concrete, and asphalt-treated, including asphaltic concrete.

CENTRAL-PLANT RECYCLING OF CEMENT-TREATED MATERIALS

Wisconsin

Several recycling projects have been performed in Wisconsin since 1972. Three miles (4.8 km) of State Highway 13 in Adams and Woods Counties were recycled in 1973. This roadway consisted of 8 in. (200 mm) of soil-cement base and 13 in. (330 mm) of bituminous surface material. Approximately one-half of the section had No. 8 (4 mm) wire mesh placed directly on the soil-cement base. This roadway was scarified to a 24-in. (610-mm) depth using a tractor with a single-tooth ripper. The scarified pavement, wire mesh, soil-cement base, and underlying sand base were hauled to a crusher and processed to meet the specifications for base material. The recycled material was hauled back to the roadway, shaped, and compacted. A 3-in. (75-mm) asphaltic concrete surface was placed on the prepared base (*36*).

Another recycling project was performed on State Highway 13 in Washburn County and U.S. Highway 2 in Ashland County. The existing pavements, consisting of paving brick, asphaltic concrete, and portland cement concrete, were broken by a crane and ball. This material was then processed through a crusher to meet a specified gradation. The resulting product was used as a base course on these roadways (*36*).

Michigan

A parking lot in Detroit has been paved with a 1.5-in. (38-mm) bituminous base containing both crushed glass and used concrete, topped by a 1-in. (25-mm) asphaltic concrete wearing surface. This material compacted well and had a good appearance (*37*).

District of Columbia

Two Washington, D.C., firms are operating crushing plants that produce usable aggregate products from pavement and building rubble. Large slabs of pavement and structural concrete are broken into smaller portions by a hydraulic breaker; then the material is fed into the portable crusher. Crushed material is screened to obtain the desired gradation. This recycled material exhibits compaction qualities somewhat better than usual subbase materials (*38*).

California

A California contractor is operating a crusher to convert asphaltic and portland cement concrete rubble into usable aggregate. Compaction tests performed on the crushed rubble indicate it is superior to many plant-run aggregates (*39*).

Another operation in California recycles portland cement concrete and asphaltic concrete paving materials for use as aggregates in a lean-mix portland cement concrete base. The salvaged material is run through a combination crusher-screening process. Reinforcing steel and other waste is manually removed and stockpiled. The aggregate is then combined with cement, water, and an air-detraining additive to form a lean concrete with an 8 percent cement content (versus 5 percent for cement-treated base). The air content was 3.5 percent, and the slump averaged 2.5 in. (60 mm). The California Department of Transportation reported the "natural" mix, without an air-detraining additive, had 13 percent air. Placement of this lean concrete was accomplished using a Blaw-Knox slipform paving machine. Seven-day compressive strengths averaged 450 psi (3100 kPa), and performance has been excellent (*40*).

Texas

Fifteen miles (24 km) of State Highway 36 in Burleson County were reconstructed in 1969. The existing roadway was a lightly reinforced portland cement concrete pavement with an asphaltic concrete overlay. The material was broken with a "headache" ball and the reinforcing steel cut with torches. After being hauled to a central location, the material was crushed and blended for use as an asphalt-stabilized base course and asphaltic concrete surface course. At the primary crusher, a worker cut the reinforcing steel. Two other workers removed loose steel from the material stream as it emerged from the secondary crusher. This steel was sold as scrap, and thus the cost of removing the steel was partially recovered.

In addition to the problems caused by the steel, the variable amount of asphaltic concrete present in the processed aggregate created air pollution problems as well as presenting minor difficulties in establishing binder demand. The asphalt quantity requirements were solved by improved plant control; however, air pollution problems were not satisfactorily solved.

Although extensive economic data have not been provided, it can be stated that the contractor did not lose money by his decision to process and use the old pavement in the new construction. Increased costs associated with rubble processing were incurred. However, these costs were largely offset by savings associated with not having to purchase and transport large volumes of high-quality coarse aggregate into the area, not to mention savings

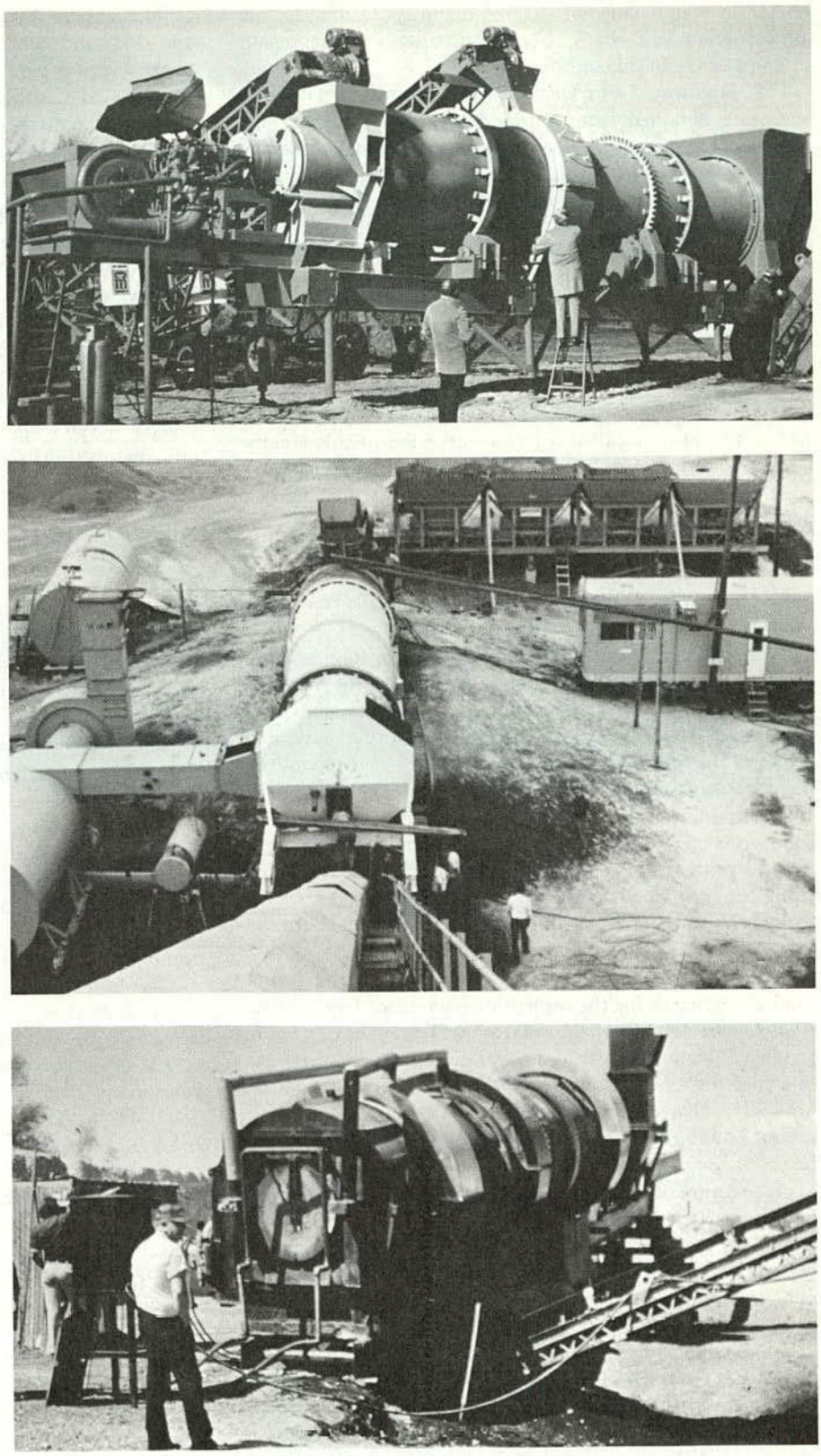


Figure 21. Central-plant recycling equipment.

related to maintenance of existing highways leading to this job if used as haul roads. Fuel requirements for aggregate drying were reduced considerably (*41*).

U.S. Highway 54 in District 4 was reconstructed using aggregate obtained from portland cement concrete. This pavement contained steel only at the joints and was thus removed and crushed with little difficulty. Aggregate produced from this source was used for asphaltic concrete surfacing and for seal-coat coverstone on the shoulder. Six and one-half percent asphalt was required with the recycled aggregate to produce the asphaltic concrete surfacing, which had a Hveem stability of 50. The performance of this pavement has been excellent since its completion in April 1972 (*42*).

A second job in District 4 was finished in February 1974 on 5.5 miles (8.8 km) of U.S. Highway 60 in West Texas (*43*). The project called for reconstruction of this Hemphill County highway, which was an 18-ft-wide (5.5-m) concrete pavement of 9-6-9-in. (230-150-230-mm) design. The reinforcing steel in the thickened edge pavement consisted of two 0.5-in. (13-mm) bars along each side with 0.5-in. by 3-ft (13-mm by 0.9-m) bars acting as tie bars between lanes. Dowels were placed in all transverse joints.

This pavement was readily adaptable to crushing because a large portion did not contain steel. Pavement breakers were used to fracture the pavement into sizes no larger than 1 ft^2 (0.09 m^2). Two men with torches cut and removed the reinforcing steel as a front-end loader removed the concrete from the road-bed.

A portable crushing plant (equipped with a jaw crusher, roll crusher, and cone crusher) and a screening plant were used to process the rubble. As the material was conveyed from the jaw crusher to the screening plant, two men picked the small amount of steel off the belt. Dust around the crusher was controlled by a water spray.

Six percent asphalt cement was mixed with the dense-graded aggregate for the asphaltic concrete surface course. The Hveem stability of this mixture was 51. The aggregate produced from the crushing operation was also used as seal-coat rock. The contractor for the project felt that he not only salvaged a valuable resource, but was able to reduce hauling costs and produce an acceptable product at less cost.

One section of Interstate 30 east of Greenville, Tex., has been constructed using old, crushed portland cement concrete as a granular base. An automatic pavement breaker was used to break 75,000 yd^2 (63 000 m^2) of 10-in. (250-mm) nonreinforced portland cement concrete into 12-in. (300-mm) sections. The sections were loaded along with 2 in. (50 mm) of the underlying sand base and hauled to a nearby overpass. Here the material was processed through a crusher. This crushed concrete was hauled to the roadway and deposited as the first layer of a base course. Finishing was accomplished using conventional methods. Performance to date has been satisfactory.

District 3 of the Texas Department of Highways and Public Transportation has recycled portland cement concrete building rubble. A detour for Kell Boulevard in Wichita Falls was constructed with 300 tons (270 Mg) of asphalt-stabilized base composed of crushed concrete rubble and field sand. Placement of this base material was accomplished with conventional equipment, and no difficulty was experienced. Although this detour was only temporary, performance was satisfactory (*44*).

Iowa

Approximately 25,000 yd^2 (21 000 m^2) of pavement were recycled by the Iowa Department of Transportation in Lyon County in 1976 (*32*). Original construction was an 18-ft-wide (5.5-m) portland cement concrete pavement placed in 1934. This concrete contained 658 lb of cement per cubic yard (390 kg/m^3). Portland cement concrete was used to widen the older pavement to 24 ft (7.3 m) in 1958. The 3-in. (75-mm) asphaltic concrete overlay was placed in 1963. The new pavement contained three different mixtures. Mixtures A and B contained recycled portland cement concrete and sand and were used to pave 9-in.-thick (230-mm) sections. Mixture C, a combination of crushed portland cement concrete and asphaltic concrete, was used as econocrete in a composite pavement section 11-in. (280-mm) thick.

The asphaltic concrete was stripped off the portland cement concrete and loaded onto trucks by a backhoe. The portland cement concrete pavement was air chiseled on about 3- to 4-ft (0.9 to 1.2-m) centers. The air chisel was attached to a small tractor-mounted backhoe. After the chiseling operation, a larger backhoe was used to pick up and load the portland cement concrete onto haul units.

A 42-in. (1.1-m) jaw crusher was used as the primary crusher. The primary crusher reduced the portland cement concrete to 5-in.-maximum (125-mm) size. A secondary portable crushing plant further reduced the material to 1.5-in.-maximum (38-mm) size. This unit contained a jaw and roll crusher. Only one stockpile was used, which resulted in some segregation.

Changes in the crushing operation included an increase in distance from the bottom of the chute out of the jaw crusher to the belt utilized for stockpiling.

The original pavement had number 5 (16-mm) smooth reinforcing bars in four longitudinal locations. No steel was used in the 2-ft by 10-in. (0.6-m by 250-mm) widening job. Steel was removed by hand at six locations: (1) on the grade during the loading operation; (2) during the loading operation for crushing in the yard (a "headache" ball was used to reduce the size of some slabs in the yard); (3) at the entry to the primary jaw crusher; (4) on the belt after primary crushing; (5) on the feed belt to the roll crusher; and (6) in the stockpile (this was a minor effort). The portland cement concrete was removed from the roadway without obtaining subbase or subgrade. About 75 to 80 percent portland cement concrete was recovered. L. G. Everist, Inc., performed the removal and crushing operation, with I. F. Jensen Company responsible for the paving operation.

The paving operation was standard except that two slipform pavers were used in the econocrete section. The first paving machine placed the 7-in. (180-mm) lift of econocrete, and the second machine placed the 4-in. (100-mm) wearing surface (Fig. 22). The econocrete contained re-

Figure 22. Recycled portland cement concrete (Iowa).

cycled portland cement concrete and asphaltic concrete. The wearing surface contained only recycled portland cement concrete. Both paving machines could be loaded from the side.

Some problems with the gate cut-off were noted during batching and while charging the aggregate. Bridging sometimes occurred in gates, and excessive fines fell out at other times. More fines exist in this mixture than in many portland cement concrete mixtures. Water-reducing admixture was used to help disperse the fines. High air contents were also noted in some mixtures. The mixture is stiff and more difficult to handle than some concrete mixtures. Rex equipment was used.

Normal concrete construction control was used. Flexural and compressive strength and freeze-thaw tests were performed; skid-resistance and roughness measurements will be made at established intervals.

Iowa has let the grading phase of a reconstruction project where old portland cement concrete will be removed and crushed for aggregate in the new roadway. This project, which is located in southwestern Iowa on Highway 2, is approximately 15 miles (24 km) long and will be completed in 1978. A second project has been completed recently on Interstate Highway 680 north of Council Bluffs, where portland cement concrete was crushed and used as subbase material on portland cement concrete shoulders (*45*).

CENTRAL-PLANT RECYCLING OF ASPHALT-TREATED MATERIALS

Iowa

1975 Project

A 0.90-mile (1.4-km) section of roadway in Kossuth County, Iowa, was recycled in April 1975. This pavement consisted of approximately 4 in. (100 mm) of asphaltic concrete on a gravel-clay base. A grader was used to scarify the pavement. Chunks of pavement were further broken up by a tractor equipped with compactor wheels. This material was hauled to the plant site where it was crushed to a maximum size of 2 in. (50 mm) (*46*).

After the pavement had been removed, the gravel-clay base material was scarified to a 4-in. (100-mm) depth over one-half the width of the roadway. This material was windrowed, moved, and stockpiled on top of the other half of the unscarified gravel-clay base. A grader was then used to cut the excavated half of the roadway down uniformly 1 ft (0.3 m) and place the excavated material on the foreslopes. The material was compacted using sheepsfoot rollers. This process was repeated on the other half of the roadway, resulting in 1,500 tons per mile (850 Mg/km) of salvaged gravel-clay base. The salvaged material was relaid, compacted, and used as a subbase material.

After the gravel-clay subbase material was in place, the crushed pavement was recycled. Mixing was accomplished by using a 10- by 30-ft (3×9-m) drum mixer with a low-efficiency wet wash. This mixer had an asphalt line inside the drum and introduced 3.5 percent asphalt by weight into a blend of 70 percent recycled pavement and 30 percent new limestone. (The old pavement contained 3.7 percent residual asphalt.) To reduce the resultant smoke, 3 percent moisture was added to the incoming pavement material. Production was maintained at 275 to 300 tons per hour (250 to 270 Mg/h) with a mix temperature of 225 F (110 C).

1976 Project

Three road segments were recycled by Kossuth County in 1976 (*47*). The first roadway is 9.5 miles (15 km) long and involves 44,838 tons (40 700 Mg) of recycled material. The Iowa Department of Transportation and the FHWA Demonstration Projects Division participated in

this project. Two other locally funded reconstruction projects totaling 5.8 miles (9.4 km) in length and involving 25,742 tons (23 300 Mg) of recycled surfacing were to be contracted at the same time. A 7-mile (11-km) local secondary resurfacing project will require 11,456 tons (10 400 Mg) of mixtures.

Preliminary testing of the crushed asphaltic concrete was performed at the Iowa Department of Transportation Central Laboratory in Ames. Four combinations of materials were tested. The Marshall testing sequence was used for evaluation. Laboratory mixtures evaluated include:

1. 100 percent recycled asphaltic concrete.
2. 80 percent recycled asphaltic concrete–20 percent sand and gravel.
3. 67 percent recycled asphaltic concrete–33 percent sand and gravel.
4. 50 percent recycled asphalt concrete–50 percent sand and gravel.

A 120- to 150-penetration asphalt cement was added in various percentages to the recycled asphaltic concrete–gravel mixtures. No softening agent or other type of additive was used. The average asphalt content of the old recycled asphaltic concrete was 5.4 percent by weight.

Three contractors bid on the Kossuth County jobs. Everds Brothers, Inc., of Algona, Iowa, was the low bidder. Reconstruction included lowering the grade, widening the pavement from about 20 to 24 ft (6.1 to 7.3 m), including shoulders, and flattening the side slopes. Recycling allowed the grade line to be lowered and the paving material to be reused. An overlay and widening job with the existing steep side slopes would have required hauling substantial quantities of material.

Two ripper teeth were used behind a dozer to break the pavement prior to loading with a front-end loader onto haul units. A stockpile of this material was created prior to crushing. A primary jaw crusher was used. A secondary roll crusher in a screening plant was used for some of the material preparation. Two-in.-maximum (50-mm) size particles were obtained.

Four percent new asphalt cement was added at the central plant to the 67 percent recycled asphaltic concrete and 33 percent gravel. The plant has been operated with up to 50 percent new material in the mixture. The plant is operated at 270 to 275 F (132 to 135 C). The average production was 210 to 215 tons per hour (190 to 195 Mg/h).

Trials have been made with oversize material from the crusher. This material is about 5-in. (125-mm) maximum size. Less pollution problems were encountered during these trials.

The pollution control system includes a deflector and a wet system. Some build-up has been noted in the duct work. Equipment is available at the job to monitor pollution problems.

A variety of changes in the plant were attempted. These alterations, almost all aimed at reducing air pollution problems, include: (1) moving the burner away from the drum mixer; (2) placing air gaps in the shroud between the burner and the drum; (3) increasing the amount of air introduced into the burner by about five times; (4) reducing the slope of the drum to 2 deg; (5) moving the heat deflector from about midway in the drum (standard location for Barber-Greene plant) to near the entry end of the drum; (6) adding flame and heat deflectors at the end of the burner shroud; and (7) introducing asphalt into the drum by a pipe at the exit end (the asphalt is normally introduced about midway in the drum).

Costs for reconstruction of pavement using the recycling approach are expected to be $62,100 per mile ($38 600/km) whereas conventional reconstruction techniques would be $72,500 per mile ($45 100/km).

1977 Project

Rohlin Construction Company recycled 43,000 tons (39 000 Mg) of hot-mix asphalt using a modified Cedarapids drum mixer plant in 1977 (*48, 49*). The modification developed by Iowa Manufacturing Company is referred to as the "drum within a drum" process (Fig. 14).

A production rate of approximately 300 tons per hour (270 Mg/h) was achieved using virgin aggregate containing 8 percent moisture and crushed, salvaged asphaltic pavement containing 4.5 percent moisture blended on a 50-50 basis. The recycled mix was discharged from the drum mixer at a temperature of 260 to 270 F (127 to 132 C). Higher production rates were achieved with a 65-35 blend (recycled-to-new aggregate) while maintaining compliance with air quality regulations. Stack particulate discharge was controlled by a wet scrubber unit.

Five and one-half percent new 200- to 300-penetration grade asphalt cement was used with this 50-50 blend mixture. Mixture design was performed by the Marshall method, which indicated a total optimum asphalt content of 9.0 percent by weight of mixture. Design parameters were: Marshall stability, 1863 lb; Marshall flow, 8 (0.01) in.; voids in mineral aggregate, 23 percent; voids filled with asphalt, 75 percent; and air voids, 6.5 percent.

Utah

1975 Project

In October 1975, the Utah Department of Transportation completed an experimental recycling project near Cove Fort. This project involved recycling of approximately 450 tons (400 Mg) of pavement material removed from Interstate 15 near Anderson Junction. The pavement consisted of 0.75 in. (19 mm) of plant-mix seal containing 6.6 percent asphalt cement and 1.5 in. (38 mm) of surface course containing 4.4 percent asphalt cement. This material was scarified and hauled to the plant near Cove Fort. The material was further broken down by the tracks of a dozer and processed through a drum mixer, where a recycling modifying agent was added. Two different percentages of modifying agent were used: 1.3 percent and 1.0 percent by weight of mixture. Approximately 3 percent water was also added. The resulting mixture was laid with conventional equipment to form a temporary connection between Interstate 70 and Utah Highway 4 near Cove Fort (*50*).

1977 Project

An 8.7-mile (14-km) section of U.S. 50 near Holden, Utah, was recycled in 1977 by Peter Kiewit Sons utilizing a modified Boeing drum mixing plant (*51*) (Fig. 13). The contractor removed the old material from the roadway by ripping with a dozer and windrowing. The material was transported to the plant site, crushed with a roll crusher, and stockpiled. A considerable portion of the material underlying the asphaltic concrete was removed, requiring some adjustments in the mixture design. Handling of the material after recycling was performed in a conventional manner. However, for equal mixture temperatures, it was noted that the recycled material was harder to "work" than a conventional mixture. The recycled material also appeared to have a greater resistance to shearing and scuffing.

The drum mixer utilized on this job was rated at 600 tons per hour (540 Mg/h) for conventional mixing. Production rates of between 275 and 375 tons per hour (250 and 340 Mg/h) were common during the project. Plant alterations included the addition of Boeings' heat shield and a positive displacement pump to replace the flow meter-type pump to control modifier quantities.

An AC-10 asphalt cement and a modifier were added to the recycled mixtures. Mixtures placed included 100 percent recycled material, 85 percent recycled and 15 percent new aggregate, and 77 percent recycled and 23 percent new aggregate.

The air pollution reduction goals of operating in the range of 20 percent opacity with 0.04 grains of particulate per dry cubic foot were not achieved consistently. Particulates were tested in a range between 0.10 and 0.12 and did not change significantly during the experimental project. Lowering the exit temperatures of the mixture to 190 to 200 F (88 to 93 C) would reduce opacity to 20 percent or below. However, this material was unsuitable for proper placement and compaction on the roadway.

Indiana

Warren Brothers, a contracting company specializing in production of asphaltic concrete and roadway construction, has performed a recycling project in Indiana. A drum mixer was used to produce a recycled material from old asphaltic pavement and coarse aggregate. One and one-half percent emulsion was added. Air pollution seemed to be the biggest problem. Warren Brothers feel that the main objective is to use existing plants with minor modifications. They have constructed a laboratory-scale model of a conventional dryer. Results of laboratory tests using the model indicate recycling is possible with conventional dryers, provided temperature control can be maintained (*33*).

Nevada

Las Vegas Paving Incorporated, which developed the RMI Thermo-matic plant and the Split-Feed Direct-Fired Method, has been active in the recycling of old asphaltic concrete pavement at McCarren International Airport in Las Vegas, on Interstate Highway 10 near Sloan, in Henderson, and generally in the Las Vegas area. The Thermo-matic plant (Fig. 21, bottom) resembles the conventional drum mixer with one important exception. Direct contact between the burner flame and combustion gases and the old asphaltic concrete is not permitted. This design produces a smoke- and fume-free effluent that complies with air quality standards.

This operation uses recycling modifiers in quantities of about 0.25 to 0.75 percent by weight of mix to soften the old asphalt. Results indicate that the quality of the recycled hot-mix is identical to that of asphalt mixes made with virgin materials (*52*).

A project primarily utilizing the Thermo-matic system was completed in 1976 on I-15 near Las Vegas. The recycling process consisted of pavement ripping, pavement removal by use of a rotary excavator, crushing with a primary jaw and roll crushers, heating, addition of an asphalt softening agent, mixing, laydown, and compaction. Each phase of the operation (pavement removal, crushing, mixing, and laydown) was scheduled to produce at the rate of about 200 tons per hour (180 Mg/h).

Cost comparisons of conventional and recycled asphaltic concrete have been prepared by Mendenhall (*53*). The cost of asphaltic concrete at the plant is $12.15 per ton ($13.39/Mg) for conventional mix as compared to $7.96 per ton ($8.77/Mg) for recycled mix. A savings of about $4.00 per ton ($4.40/Mg) may be achieved (Fig. 23).

This form of recycling offers not only the cost advantage but also a savings in energy and natural resources. The energy utilization of the recycling operation may be only 40 percent of that consumed in a conventional asphaltic concrete construction operation (*52*).

Virginia

Warren Brothers has performed an experimental recycling project involving about 7,000 tons (6 400 Mg) of recycled hot mix on U.S. 1 near Richmond, Va. (*54, 55*). The old asphaltic pavement, about 4- to 6-in. (100 to 150-mm) thick, was removed by three different techniques. Two Pettibone machines were used on a portion of the project to pulverize the pavement in place. On another portion, a Galion RP-30 was used to remove the material. Other sections of pavement were processed by ripping and removal from the roadway followed by crushing in a central plant. Considering the traffic condition of this project, central-plant crushing may be the preferred operation of the three methods used.

A Warren Brothers, 120-ton-per-hour (110 Mg/h), conventional batch plant built in 1925 was used for heating and mixing. This plant had several modifications: (1) the burner was moved back 1 ft (0.3 m) and additional air introduced; (2) about 3 ft (0.9 m) of flights were removed from the fire end of the drum; (3) a fluidized sand bed developed by M.I.T. was used on a very limited basis for air pollution purposes; and (4) hot screens were removed.

The resulting mixture, containing an additional 1.3 percent AC-10 asphalt cement, has been laid on a portion of the project. Problems involving air pollution and clogging of duct work were encountered on the project and contributed to the low-softening-point bituminous material used for one of the recycled asphaltic concrete layers.

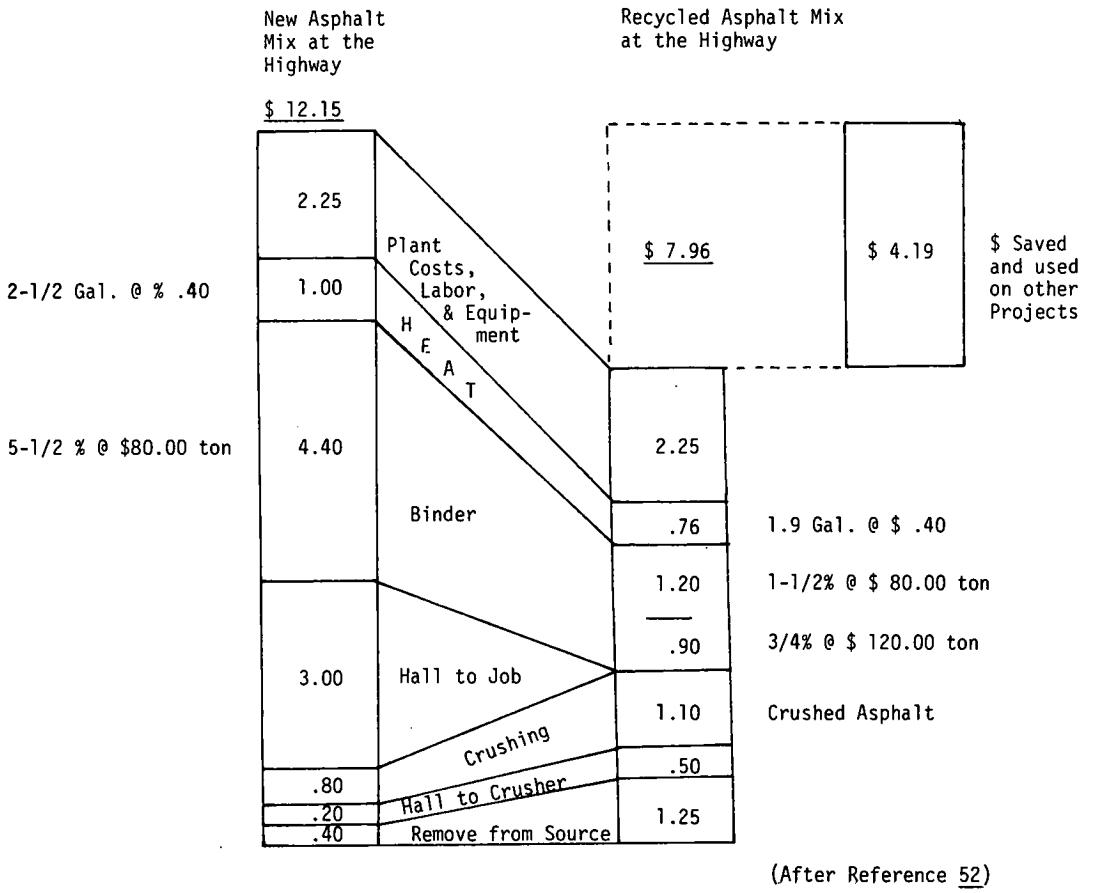


Figure 23. RMI plant costs per ton ready to lay.

The fluidized sand bed was very successful in removing all blue smoke from the exhaust system. Production rates of about 60 percent of rated capacity were achieved on the project.

Small-scale Warren Brothers recycling projects have been performed in Farmington, N. H.; Greensborough, N. C.; and Richmond. Va. Little build-up of fines was noted on these projects.

Texas

1974 Project

In early 1974, the Texas State Department of Highways and Public Transportation decided to use a portion of the asphaltic concrete removed from U. S. Highway 83 in McAllen and recycle it as an experimental project. The asphaltic concrete was removed in the conventional manner, using a "headache" ball, rippers, and front-end loaders. It was hauled to the contractor's plant site (which was also at his raw-aggregate source) and processed through a primary crusher to approximately 2.5- to 3-in. (60 to 75-mm) top size. The material was then run directly into a drum-dryer plant. Preliminary and cursory laboratory analysis indicated that 1 to 1.5 percent of additional asphalt (AC-20) would probably be sufficient, but it turned out that about 2 percent (AC-20) was required to get the desired mix characteristics. The material coming from the plant had the appearance of a normal mixture and its workability was very similar. This material was hauled to a roadside park on U. S. Highway 281 in North Hidalgo County and placed next to a conventional surface mixture for future observation. Unfortunately, the traffic count on this pavement will be rather low; hence, it will be some time before its performance under traffic will be known. Air pollution was not a problem on this project (*44*).

1975 Project

In the spring of 1975, a 1.4-mile (2.3-km) section of U. S. Highway 84 was recycled on an experimental basis by District 8 of the Texas State Department of Highways and Public Transportation (*56*). This section consisted of a hot-mix asphaltic concrete surface on a flexible base. After the material was scarified, two methods of crushing the rubble were used. With the first method, material was hauled to a primary crusher and processed. A conventional pugmill plant was used to recycle this material. The addition of ½ to 1 percent asphalt by weight to the recycled pavement produced a material with a good consistency.

The second crushing method employed in-place crushing using a tractor-drawn grid roller. This process allowed the contractor to insert moisture into the material to ob-

tain a more uniform moisture content, which aided mixing and improved air quality. A 2.5-in. (63-mm) screen was positioned on the old cold-feed conveyor to remove any large-size chunks of pavement before processing in the drum mixer.

Five combinations of new and recycled material were tried. The first trial consisted of 20 percent new base material and 80 recycled pavement with the addition of 5 percent by weight of asphalt emulsion. This mixture laid well and had all the appearances of a successful mix. The second trial consisted of 50 percent new base material, 50 percent recycled pavement, and 6 percent asphalt emulsion by weight. This mixture was placed on the roadway with no difficulty. The third trial consisted of 60 percent new base material, 40 percent recycled pavement, and 6 percent AC-10 asphalt by weight. This mixture produced excessive dust and required addition of water. Placement of this mixture was accomplished with little difficulty. The fourth mixture consisted of 70 percent new base material, 30 percent recycled pavement, and 7 percent AC-10 asphalt by weight. This mixture produced a large quantity of smoke but was placed with a minimum amount of difficulty. The final trial was composed of 100 percent recycled pavement and 4 percent AC-10 asphalt by weight. This mixture did not have a good consistency and placement was difficult.

The major problem encountered in this experimental operation was air pollution. The pugmill plant was equipped with a bag house. This, however, could not remove the "blue smoke" produced by exposing the asphalt-rich old pavement to direct flame. The drum mixer was equipped with a water bath. This also was unable to remove the smoke from the exhaust stack. Temperatures as low as 200 F (90 C) were maintained in an effort to reduce this smoke (*56*).

1976 Project

In 1976, a drum mixer manufactured and modified by Boeing was used to recycle asphaltic concrete to overlay 1.5 miles (2.4 km) of a secondary road near Mission, Tex. (*57*) (Fig. 13). Modifications included a ceramic grid, the flame moved away from the drum, and water sprayed onto the crushed asphaltic concrete. Asphalt cement (AC-3), or flux oil and a recycling modifier, were added to the recycled asphaltic concrete to produce these mixtures. The most successful trial from emission and mix-property standpoints appeared to be that mixture produced with 2 to 2.5 percent asphalt cement. This mixture was produced at a rate of 100 to 150 tons per hour (90 to 140 Mg/h) at an acceptable temperature and with acceptable emissions. The mixtures made with flux oil and the modifier had excessive emissions. Portions of the compacted recycled mixture made with flux oil raveled shortly after opening to traffic. The flux oil and modifier were used as softening agents.

1977 Project

In 1977, a drum mixer plant manufactured and modified by Boeing was used to recycle asphaltic concrete on Interstate Highway 20 in District 8 of the Texas State Department of Highways and Public Transportation (Fig. 13). Modifications to the plant included a heat shield and introduction of the aggregate to the underside of the drum. Crushing of the old asphaltic concrete was performed at the plant site. Some of the existing base course was utilized in the recycled mixture plus additional new aggregate. Water added to the stockpiles before recycling helped control opacity.

The recycled mixture was used as a base course and did not contain a modifier except for a short experimental section. Mixture design was based on the Hveem stabilometer and the Texas black-base design method.

Additional experiments on a small scale have been conducted by Boeing in North Dakota and Arizona. The purpose of these trials was to improve emissions and to test the durability of the grate materials. A discussion of the Arizona project follows.

Arizona

Arizona recycled 25,200 tons (22 900 Mg) of asphaltic concrete in 1976. The recycled material was used to overlay 5.4 miles (8.7 km) of Highway 666 from Interstate 10 north to the Graham County line.

Equipment used in the salvaging operation included a 180-hp (134-kW) grader with blade and ripper, a 6-yd^3 (4.6-m^3) loader, four 19-yd^3 (14.5-m^3) trucks, and a 385-hp (287-kW) dozer. The grader ripped the 3- to 5-in. (75 to 125-mm) asphaltic concrete mat and bladed the material into a semi-windrow, the loader removed the material from the roadbed and placed it in trucks, and the dozer pushed the material into a stockpile after it was dumped. The salvaged asphaltic concrete was crushed by state maintenance forces using a Pioneer Model 358S roll crusher.

In August 1976, 100 yd^3 (76 m^3) of crushed asphaltic concrete were run through a modified drum mixer for test purposes. These tests were inconclusive; however, the full-scale job was started in March 1977 by D. C. Speer Construction Company.

A Boeing drum mixer with several modifications was used (Fig. 13). A special steel alloy "Pyro-Cone" 6 ft (1.8 m) in diameter was one of the plant modifications, together with a high-speed under-feed belt to "throw" the cold feed material into the drum about 3 ft (0.9 m) from the burner. A number of modifications were made during the project. The production and exit mix temperatures that produced acceptable air quality (40% opacity) were as follows:

Mix Temperature, F (C)	Production, tons/hr (Mg/h)
235(113)	245(222)
225(107)	280(254)
205(96)	325(295)

The mixture produced contained 80 percent recycled asphaltic concrete and 20 percent coarse aggregate. The

amount of binder used with this mix varied during the project. The best combination appeared to be AR-2000 asphalt cement containing 50 percent modifier by weight added to the mix in the amount of 2.7 percent. This resulted in 5.3 percent asphalt in the mix. This combined binder (new asphalt, old asphalt, and modifier) had a penetration of 64 and a viscocity of 2180 poises (218 Pa·s) at 140 F (60 C). The old asphalt had a penetration of 7.

A net saving of $4.02 per ton ($4.43/Mg) was achieved on this job when a comparison was made between conventional asphaltic concrete and the recycled asphaltic concrete. The cost of ripping, loading, hauling, crushing, and stockpiling was $1.49 per ton ($1.64/Mg) (*58*).

Arizona had additional recycling projects in 1977 and 1978. The state also has performed tests on several modifiers to investigate their potential use in these recycling operations.

Minnesota

1976 Project

A mile (1.6 km) of urban street in Maplewood, Minn., was reconstructed using central-plant recycling. The old roadway was 48 ft (14.6-m) wide and had 12 in. (300 mm) of gravel base and 4 in. (100 mm) of plant-mixed bituminous surfacing. The new roadway is a 4-lane divided expressway and contains 7 in. (180 mm) of recycled bituminous base, 1.5 in. (38 mm) of recycled bituminous leveling course, and a ¾-in. (19-mm) wearing course made with taconite tailings (*59*).

The contractor (C. S. McCossan, Inc.) tried several methods of scarifying and reducing the size of the asphaltic concrete. The most cost-effective method was to scarify and windrow the old asphaltic concrete with a grader and put the material through an in-plant crusher. The salvaged material was crushed to 1.5 in. (38 mm) maximum with conventional crushing machinery.

The mixing process consisted of superheating (400 to 450 F; 204 to 232 C) aggregate in the dryer and adding the crushed asphaltic pavement to the hot aggregate in the pugmill. Three percent asphalt cement was added to satisfy the mixture of 50 percent aggregate and 50 percent recycled asphaltic concrete.

Heated storage bins were used for the recycled mixture to accommodate the contractor's schedule. This storage probably enhanced the heat exchange between the aggregate and the recycled asphaltic concrete. However, the project engineers were unable to distinguish any difference between the mixture hauled directly out of the pugmill and that hauled from the storage bins.

This project was a major breakthrough in that a process was developed that would allow use of conventional pugmill plants. Since the completion of the Maplewood project in 1976, the same technique has been successfully attempted at the Warren Brothers experimental project in Richmond, Va. Air quality was not a problem using this method.

1977 Project

Forty miles of paved asphaltic concrete shoulders on I-94 near Fergus Falls, Minn., were recycled in 1977 by Duininch Brothers and Gilchrist utilizing a Barber-Greene plant (*60*) (Fig. 15). The contract required removal of 2 in. (50 mm) of the existing asphaltic concrete and 2 in. of the untreated aggregate base.

Pavement removal was accomplished by ripping the joint between the pavement and the shoulder and by ripping the shoulder down the center using a road grader. The existing hot-mix was then easily picked up with a front-end loader. The untreated aggregate base was picked up with a subgrade trimmer, which also established grade for placement of 4 in. (100 mm) of recycled asphaltic concrete.

The salvaged asphaltic pavement was crushed with a gyrasphere and stockpiled. The salvaged base course was introduced into the drum mixer in conventional fashion while the recycled asphaltic concrete was fed into a 10- × 40-ft (3- × 12-m) drum from the mix discharge end with an 18-in. (460-mm) slat conveyor. Approximately 45,000 tons (41 000 Mg) of mixture were produced with this 50-50 blend of reclaimed, untreated base and asphaltic concrete.

The recycled mixture was discharged from the drum at a temperature of 250 to 270 F (121 to 132 C) at a production rate that averaged 300 tons per hour (270 Mg/h). Stack opacity, in most cases, was less than 10 percent. No tests were taken on stack particulate emissions. Paving was performed in conventional manner.

Future Projects

Several hot-mix recycling projects are scheduled or have been recently completed in Arizona, California, Iowa, Minnesota, Nevada, Oregon, Texas, Utah, and Washington (*61*). Boeing, Iowa Manufacturing, Barber-Greene, and CMI equipment have been used on these projects. Results from these projects are not available to include in this synthesis.

RECYCLING MODIFIERS

As discussed previously, recycling modifiers have been used on a number of projects. These modifiers are normally aromatic oils that soften the old asphalt cement. Existing commercial suppliers are Koppers Company, Pax International, Shell Oil Company, and Witco Chemical Company. Other companies that manufacture modifiers are Arizona Refining Company, Ashland Petroleum Company, Chevron, Lion Oil Company, Mobil Oil Company, and Phillips Petroleum Company. Addresses for these companies and others are given in Appendix B.

SUCCESSFUL HOT CENTRAL-PLANT RECYCLING

The RMI Thermo-matic unit and the approach used in Maplewood, Minn., can successfully recycle asphaltic concrete in a hot process without significant emissions. The plant alterations presently proposed for drum mixer plants have for the most part solved the emissions problems provided (a) 30 to 50 percent new aggregate is used in the

recycled mixture, (b) water is added to the recycled material, (c) production rates are reduced, and (d) mixture exit temperatures are controlled. These major equipment improvements have been made primarily by Barber-Greene, Boeing, CMI, Iowa Manufacturing, and Mendenhall.

The pollution control equipment (fluidized sand bed) developed at Massachusetts Institute of Technology offers a system in prototype form for control of emissions from recycling operations. This system has been used on a trial basis by Warren Brothers.

Because most projects have been of an experimental nature and of short duration, it is difficult to determine cost and energy consumption data. A cost saving on the order of $4.00 per ton ($4.40/Mg) and a 20 to 30 percent energy saving may be possible in hot central-plant recycling of asphaltic concrete.

TWO OTHER CATEGORIZATIONS

Material and Product

Categorization of recycling procedures based on the type of material to be recycled and the end product it is to produce has been followed in references that summarize pavement recycling efforts (*62*). Table 16 indicates a possible method of categorizing recycling operations using this concept. Using this approach, a Transportation Research Board workshop on "Optimizing the Use of Materials and Energy in Highway Construction," held in November 1975, indicated: (a) the extent and use of the various approaches, (b) if the recycling approach was implementable, (c) the energy required on a relative basis, and (d) the relative cost of the operation (Table 16) (*62*). Based on this table, it is evident that the most commonly used recycling procedures are the following:

1. Surface recycling using heater-scarifiers.
2. In-place recycling involving unstabilized bases.
3. In-place recycling including use of lime, cement, or asphalt as a stabilizer.
4. Central-plant operations involving reprocessing of portland cement concrete and asphaltic concrete for asphaltic concrete mixtures.

Pavement Structural Benefit

Categorization based on pavement structural benefit is a third possibility for organizing pavement recycling approaches. Such a categorization is shown in Figure 24. The benefits of this grouping include simplification of recycling processes to provide guidelines for the cost, life, and energy requirements for the various recycling alternatives.

TABLE 16

RECYCLING OPERATIONS

Recycling						
From	To	Construction Operation	Extent of Use	Implement	Energy Required	Relative Cost
Untreated base, subbase, and thin surface	Untreated base	In place	Common	Yes	Low	Low
	Treated base	In place	Common	Yes	Low	Moderate
	Untreated base	Central plant	Rare	Yes	Moderate	High
	Treated base	Central plant	Rare	Yes	High	High
Treated base, subbase, and thin surface	Untreated base	In place	Common	Yes	Moderate	Moderate
	Treated base	In place	Common	Yes	Moderate	Moderate
	Untreated base	Central plant	Rare	Yes	Moderate	High
	Treated base	Central plant	Rare	Yes	High	High
Asphalt-aggregate surface mixture	Untreated base	In place	Common	Yes	Low	Low
	Treated base	In place	Common	Yes	Moderate	Moderate
	Untreated base	Central plant	Limited	Yes	Moderate	High
	Treated base or surface	Central plant	Rare	Yes	High	High
Portland cement concrete surface	Untreated base	In place	Limited	Yes	Low	High
	Treated base	In place	Rare	Probably	High	High
	Untreated base	Central plant	Limited	Yes	Moderate	High
	Treated base or surface	Central plant	Limited	Yes	High	High
Existing base, subbase, and thin surface plus new material	Untreated base	In place	Limited	Yes	Moderate	Low
	Treated base	In place	Limited	Yes	High	Moderate
	Untreated base	Central plant	Rare	Yes	Moderate	High
	Treated base	Central plant	Rare	Yes	High	High
Heater-planer		In place	Common	Yes	High	Moderate
Heater-scarifier		In place	Common	Yes	High	Moderate
Heater-scarifier-remix		In place	Common	Yes	High	Moderate

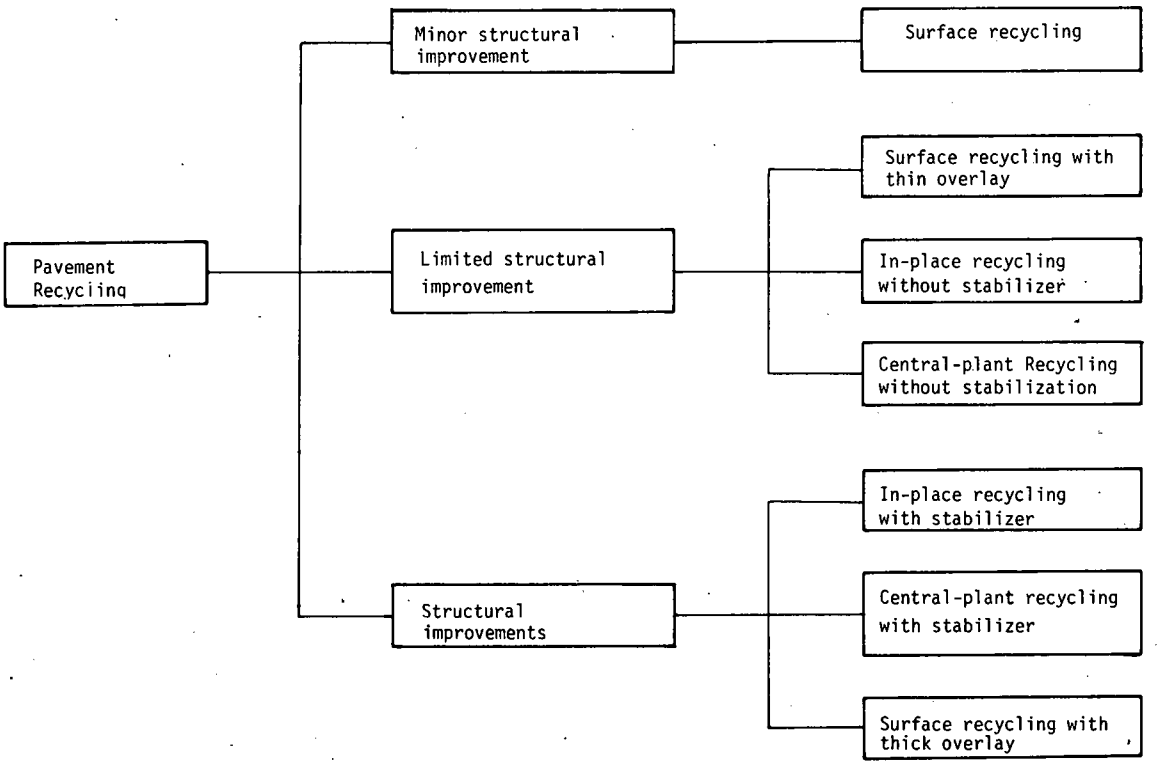


Figure 24. Categorization of recycling approaches based on pavement structural benefit.

CHAPTER SIX

RECYCLING OF OTHER MATERIALS

OTHER HIGHWAY MATERIALS

Significant quantities of guardrails and sign blanks have been recycled by state highway departments (Table 1). Some culverts have been reused, and a limited amount of motor oil has been recycled. Many states sell used motor oil to private concerns who recycle it or resell it for fuel. Used motor oil has been used as the fuel in hot-mix asphalt batch plants in Texas and Kansas. Several states have indicated the reuse of sign posts and delineator posts. Miscellaneous items recycled by states are given in Table 17. Of the items previously described, recycling of guardrails and sign blanks offers the largest economical advantage. Machinery to straighten guardrails is commercially available and has been used in Massachusetts, Maine, and Texas, among other states (*63, 64*). These trailer-mounted machines can be towed from location to location and can provide savings of from $2,000 to $4,000 a day (*63*).

Operation of a trailer-mounted guardrail and delineator post straightener in District 2 (Fort Worth) of the Texas State Department of Highways and Public Transportation has provided approximately 80 percent reuse of all damaged guardrails. The cost of the recycling operation varies from $1.75 to $2.00 per 12-ft, 6-in. (3.8-m) length of guardrail. Recycling of delineator posts costs about $1.60 each. Most of the steel-plate guardrail and delineator posts used in the Fort Worth District are galvanized. The machine will damage the galvanizing slightly; however, the extent of the damage is not severe enough that the rail needs to be regalvanized or painted (*64*).

Costs for recycling guardrails in the Corpus Christi District are $0.45 per ft ($1.48/m). This cost includes machine rental and labor costs to straighten the guardrail. New guardrails presently cost $1.57 per foot ($5.15/m) (*64*). The guardrail and delineator post straightener machine used in Texas is shown in Figure 25.

TABLE 17

MISCELLANEOUS ITEMS RECYCLED BY STATES

STATE	ITEM
Georgia	Guardrail Posts and Anchor Systems Structural Steel Ground Tires Aluminum Handrail Light Standards Traffic and Railway Crossing Signalization
Maine	Rubberized Slurry Made From Shreds Obtained in Smoothing Tire Casings Prior to Recapping
Oregon	Paper
South Carolina	Trichloroethane
Texas	55 Gallon Paint Drums
Wisconsin	Topsoil Storm Sewer Pipe Fencing Chain Link Fence Aluminum Railing Light Poles Drainage Structure Castings Underdrain Pipe Signal Cabinets Lighting Luminaires Electrical Conduit Reflectors
Wyoming	Fence

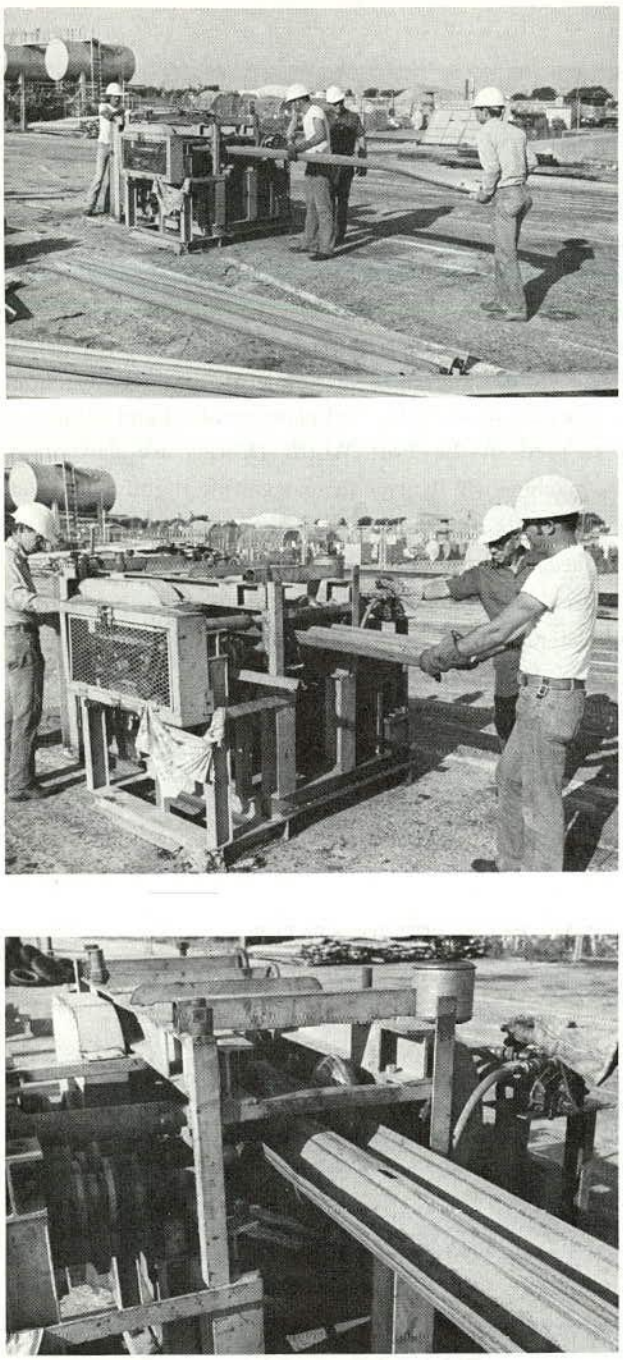


Figure 25. Texas guardrail and delineator post straightener.

Highway litter recycling was the subject of a report prepared for the Federal Highway Administration by the Texas Transportation Institute (*65*). The general conclusions indicated that highway litter combined with other wastes can be used and is in sufficient quantity for aggregate replacement in highway construction and maintenance near large urban areas. In rural areas and small and medium-size cities, however, use of sanitary landfills is a considerably less expensive method of disposal than is central processing.

The over-all economics of the use of highway litter indicate that, even in its best use, highway litter has a *negative value;* that is, it costs more to collect and process than it is worth in its most economical use. The litter must be processed prior to use as an aggregate replacement (*65*).

NONHIGHWAY MATERIALS

A recent study conducted by Valley Forge Laboratories (*66*) and the University of Illinois has delineated the types and amounts of waste materials that are potential replacements for highway aggregates. These materials have been classed in terms of industrial wastes, mineral wastes, and domestic wastes. Annually about 3.5 billion tons (3.1 Pg) of these solid wastes are being generated. The materials with the largest available tonnage include fly ash, blast furnace slag, steel slag, foundry wastes, coal refuse, copper tailings, dredge spoil, phosphate slimes, taconite tailings, and iron ore tailings. Another potentially large amount of waste solids may become available in the form of scrubber sludges when power generating facilities begin to use limestone scrubbers for SO_2 removal from stack gases.

Many of the more abundant materials are located in rural areas or in very localized areas or regions of the country; thus, the available market is limited.

In addition to use as an aggregate or filler, many wastes and by-products have potential for use as a binder. Among the more important materials in this category are sulfur and fly ash. Sulfur is expected to increase in supply because of pollution abatement programs and the necessity to burn the higher-sulfur crudes and coals. Fly ash may be used as a partial replacement for portland cement and as a pozzolan in lime and portland cement concrete mixtures. Other potential binders may emerge from wood byproducts in the form of resins or lignins or from pyrolysis of wood or other materials.

Table 18 lists 53 waste materials that have potential for use as aggregate, filler, partial binder replacement, or binder. The probable use of each of the materials in terms of a binder or aggregate is given, with the annual quantity produced (where the information was available), the extent of the material from a national distribution standpoint, an assessment of additional energy required to use the material in the roadway, an estimate of the cost, whether the material has an implemental use, and an assessment of the research requirements (*62*). The research requirements give an estimate of whether a long-term or short-term payoff is likely. The assessment of energy requirements and costs is relative to other materials within the table. It should be noted that sufficient information was not available to complete the table for many materials.

Information obtained from the state survey conducted as part of this synthesis indicated that fly ash and slag are used in significant quantities by a number of states. Use of fly ash and wet bottom boiler ash is expected to increase in the western United States as lignite becomes a popular fuel for generating electricity (*67*). Most of the fly ash is presently used as a partial cement replacement. Both slag and wet bottom boiler ash are presently used.

TABLE 18

WASTE MATERIALS (*62*)

Material	Probable Use		Annual Quantity[a] ($\times 10^6$ tons)	Extent of Material	Additional Energy Required	Cost	Potential Use	Research Required[b]
	Binder	Aggregate						
Sulfur-asphalt	X	X	NA	National	Low to moderate	Moderate	Probable	Yes, short
Sulfur-primary binder	X		NA	National	Moderate	High	No	Yes, long
Fly ash-lime-cement	X		32	Regional	Moderate	Moderate	Yes	Yes, short
Fly ash, sintered		X	32	Regional	High	High	Yes	Nominal
Fly ash, fill		X	32	Regional	Low	Low	Yes	Nominal
Mine tailings		X	NA	National	Moderate	Moderate	Yes	Nominal
Crusher wastes		X	NA	National	Low	Low	Yes	Nominal
Incinerator residue		X	10	Local	Moderate	Low	Yes	Yes, short
Rubber tires, granulated	X	X	3 to 5	Local	Moderate	Moderate	Yes	Nominal
Rubber tires, vulcanized	X	X	3 to 5	Local	Moderate	Moderate	Yes	Nominal
Waste glass		X	12	Local	Low	High	Yes	None
Blast furnace slag		X	30	Regional	Low	Moderate	Yes	None
Steel slag		X	10 to 15	Regional	Low	Moderate	Yes	None
Dry bottom ash		X	10	Regional	Low	Moderate	Yes	None
Bricks		X	NA	Local	Low	Low	Yes	Nominal
Tile			NA	Local	Low	Low	Yes	Nominal
Stack dust		X	NA	Local	Low to moderate	Low	Yes	Nominal
Stack dust	X		NA	Local	Low	Low	Probable	Yes, short
Resins and lignins	X		NA	Regional	Unknown	Unknown	No	Yes, long
Sulfate and sulfite sludges	X	X	5 to 10	Regional	Low	Low	Yes	Yes, long
Scrubber sludges		X	NA	National	Low	Low	Yes	Yes, short
Slag cements	X		NA	Regional	Moderate	Moderate	Yes	Yes, short
Waste oils	X		NA	National	Low to moderate	Low	Yes	None
Sulfuric acid	X		NA					
Salt water	Low		NA	Local	Low	Low	Yes	Nominal
Oil shale asphalt								
Plastic wastes	X	X	2.5 to 3.0					
Sewage sludge		X	8 to 10					
Wood chips and saw dust			NA					
Pyrolysis	X	X	NA	National	Unknown		Yes	Yes, long
Wet bottom boiler slag		X	5	Regional	Low	Moderate	Yes	None
Foundry wastes		X	20	Local	Low to moderate	Moderate	Yes	Yes, short
Alumina red and brown mud	X	X	5 to 6					
Phospogypsum	X		5					
Phosphate slimes		X	20					
Anthracite coal refuse		X	10					
Bituminous coal refuse		X	100					
Asbestos tailings		X	1					
Copper tailings		X	200					
Dredge spoil		X	300 to 400					
Feldspar tailings		X	0.25 to 0.50					
Gold mining waste		X	5 to 10					
Iron ore tailings		X	20 to 25					
Lead tailings		X	10 to 20					
Nickel tailings		X	NA					
Phosphate slag		X	4					
Slate mining		X	NA					
Waste taconite tailings		X	150 to 200					
Zinc tailings		X	10 to 20					
Smelter waste		X	NA					
Building rubble		X	20					
Ceramic wastes		X	NA					
Rice hulls								
Concrete pipe								

Note: 1 ton = 907 kg.

[a]NA = not applicable. [b]Short or long indicate whether the research has a short- or long-term payoff.

Mining wastes are used by a number of states (Table 1). The types of mining wastes, the approximate quantities, and their end uses are given in Table 19. In addition, significant quantities of aggregate are produced from gold-dredge tailings in California.

Recycling of glass into the highway received national recognition in the early 1970s. However, glass manufacturers are willing to pay \$15 to \$20 per ton (\$16.50 to \$22.00/Mg) for waste glass delivered to their plant. Thus, glass must be considered an expensive aggregate (*65*).

Small quantities of recycled tires are being used in highways. Rubber reclaimed from tires has been used as an addition to asphalt. Another use of the material is as a stress-relieving interface placed between the old pavement and a new asphaltic concrete overlay to reduce reflection cracking (*10*). Relatively large amounts of recycled rubber are also being used in surface layers (*68*). This material has been used mainly in Arizona to date.

Incinerator residue obtained by burning municipal waste has been used as an aggregate for a bituminous base pavement in Houston, Tex. (*69*). Results of laboratory and field evaluations show that the "littercrete" pavement meets current specifications for asphalt-stabilized materials and can be constructed using conventional equipment and technology. The high cost of aggregates in certain urban areas makes this alternative aggregate supply economical.

TABLE 19

MINING WASTES PRESENTLY RECYCLED BY STATES

State	Type of Mining Waste	Approximate Quantity 1971-1976, Tons	Use
Alabama	Strip mining wastes	N.A.*	Shoulder material
Idaho	N.A.	500,000	N.A.
Iowa	N.A.	N.A.	Temporary surfacing material
Kansas	Chert from lead and zinc mines	$3 - 5 \times 10^6$	
Minnesota	Taconite	250,000	N.A.
Missouri	Flint	600,000	N.A.
New York	N.A.	Large quantities	N.A.
Oklahoma	N.A.	Small quantities	N.A.
Oregon	N.A.	Small quantities	N.A.
Pennsylvania	Coal	2,200,000	N.A.
Washington	Obtained from tunnel	500,000	

*Quantity or information not available.

CHAPTER SEVEN

RESEARCH AND CONCLUSIONS

RESEARCH NEEDS

Table 20 gives an incomplete summary of research recently completed or scheduled in the area of pavement recycling, waste materials, and byproducts. In general, the majority of the future research effort should be expended on those materials in large national supply that are promising aggregate replacements and preferably those that may become binder supplements or primary binders.

Based on a review of pavement recycling experience to date, the following research items have been identified:

1. Air pollution associated with recycling asphalt-stabilized mixtures in hot-mix operation through a central plant has been identified as a top-priority research item. A complete solution to the problem will require involvement of governmental agencies, research institutions, equipment manufacturers, and contractors.

2. Guidelines need to be established that will assist the engineer in the decision-making process concerned with recycling. For example, what types of pavement and materials tests should be performed to determined if a mixture is suitable for recycling?

3. Costs and energy consumption associated with recycling operations must be established if the engineer is to select the proper rehabilitation alternative. Limited cost and energy data are presently available.

4. Properties of recycled mixtures should be determined and compared with both conventional mixtures and properties of the mixture before recycling. The effect of modifiers on recycled mixtures is of importance.

5. In-place recycling equipment needs to be improved to reduce equipment maintenance costs. Pulverization equipment is the most critical item in need of improvement.

6. The type and amount of modifying agents to add to recycled asphaltic mixtures should be determined. Private industry is expected to develop materials; however, testing and evaluation techniques to determine long-term effects of these additions should be developed.

7. Modifiers need to be developed that will both soften the asphalt and improve its resistance to water-caused deterioration.

TABLE 20

SUMMARY OF RESEARCH IN THE AREA OF WASTE MATERIALS, BY-PRODUCTS, AND RECYCLED PRODUCTS (*62*)

Agency	Status or Year Started	Title
FHWA	Completed	Highway Litter in Highway Construction and Maintenance
FHWA	Completed	Sulfate-Fly Ash-Lime-Aggregate Mixtures at Dulles Airport
FHWA	Completed	Production of Synthetic Aggregate From Municipal Incinerator Residue
FHWA	Completed	Rubber-Asphalt Binder for Seal Coat Construction
FHWA	Under way	Incinerator Residue in Bituminous Base Construction
FHWA	Under way	Lime Treatment of Incinerator Residue for Base
FHWA	Under way	Technology for Use of Waste Sulfates as Aggregates and Binder
FHWA	Under way	Technology for Use of Incinerator Residue as Highway Material
FHWA	Under way	Use of Waste Sulfate for Remedial Treatment of Soils
FHWA	Under way	Power Plant Bottom Ash in Black Base and Bituminous Surfacing
FHWA	Under way	Availability of Mining Wastes and Their Potential for Use as Highway Material
FHWA	Under way	Production of Synthetic Aggregate by Fusion of Incinerator Residue
FHWA	1975	Advanced Technology Materials Applied to Guideways, Highways, and Airport Runways
FHWA	1975	Extension and Replacement of Asphalt Cement with Sulphur
FHWA	1975	Demonstration Project on Recycling of Asphalt Pavements
FHWA	1975	Demonstration Project No. 37, Discarded Tires in Highway Construction
FHWA	1975	Demonstration Project No. 39, Recycling Asphalt Pavements
FHWA	1976	Evaluation of Wood Resins and Lignins as Substitutes for Asphalt
NCHRP	1976	The Reuse of Materials in Pavement Rehabilitation
NCHRP	1976	Upgrading Poor Performance Aggregates for Use in High Type of Pavements
NCHRP	1976	Guidelines for Recycling Pavement Materials
FHWA	1977	Materials and Techniques for Improving Engineering Properties of Sulphur
FHWA	1978	Rapid Removal Methods for Portland Cement Concrete Pavement
FHWA	1978	Equipment for Economical Recycling of Highway Materials for Maintenance
FHWA	1978	Development of Pilot Manufacturing Process for New and Improved Aggregate
FHWA	1978	Development and Design of Flexible Sulphur-Concrete Paving Mixtures
FHWA	1978	Development and Design of Rigid Sulphur-Concrete Paving Mixtures
FHWA	1978	Demonstration Project No. 47, Recycling Portland Cement Concrete Pavement
FHWA	1978	National Experimental and Evaluation Program No. 22, Pavement Recycling
FHWA	1978	Test for Efficiency of Mixing Recycled Asphalt Pavements Softening or Rejuvenating Agents for Recycled Bituminous Binders
FHWA	1978	Data Bank for Recycled Bituminous Concrete Pavements
FHWA	1979	Materials Characterization
FHWA	1979	Sampling and Testing of Materials to be Recycled
FHWA	1979	Rapid Test Methods
California	Under way	Fill Stabilization with Nonbiodegradable Wastes
Arkansas	Completed	Production of Binders and Fillers from Cellulosic and Man-made Polymeric Wastes Generated in Arkansas
North Dakota	Completed	Laboratory Evaluation of Lignite Fly Ash in Portland Cement Concrete
Arizona	Under way	Utilization of Waste Boiler Ash in Highway Construction in Arizona
Arkansas	Completed	Use of Fly Ash as Fill and Base Material in Arkansas Highways
Arizona	Under way	Investigation of Chemical and Physical Properties of Rubber-Asphalt Mixtures
Texas	Under way	Engineering, Economy, and Energy Considerations in Design, Construction, and Materials
Utah	1978	Evaluation of Softening Agents for Recycled Asphalt Concrete

8. Construction quality control measures for pavement recycling need to be defined, as well as uniformity of construction using the various recycling techniques.

9. Field performance of recycled pavement sections needs to be monitored by a selected agency. Performance should be compared with pavements constructed with conventional materials.

10. Strength coefficients should be established for recycled materials. These coefficients should be suitable for use in pavement thickness design methods.

11. Training programs should be established in the area of pavement recycling. These programs should include data on equipment, techniques, cost, energy, pavement design considerations, etc.

12. Pavements should be designed such that rehabilitation techniques are energy efficient and as inexpensive as possible. Pavements may have to be designed with the surface as the weak link in the structure because repair can be effected most easily at the surface. For example, one concept to investigate is the design and construction of the surface material for easy recycling.

NCHRP Project 1-17, "Guidelines for Recycling Pavement Materials" (*6*) and the proposed FHWA FCP can be expected to answer several of the identified items.

Sulfur research efforts appear to be essential and should continue. This research should be focused in the following areas:

1. Use of sulfur as an asphalt extender or supplement.
2. Use of sulfur as a mineral filler.
3. Use of sulfur as a primary binder.
4. Development of equipment to handle sulfur-aggregate systems.
5. Use of foamed sulfur.
6. Environmental quality problems associated with sulfur.

Fly ash is a promising binder. Substantial research has been conducted in this area (*54*). Implementation and the resolution of certain problems unique to particular fly ash supplies appear to be in need of additional research efforts. The use of lignins and sulfites as binders is in need of long-term research efforts.

Promising areas of research associated with aggregate replacements are in the areas of fly ash, bottom ash, blast furnace slag, steel slag, and mining wastes. These materials are presently being utilized; however, optimization of their

use in terms of material conservation and energy conservation has not been intensively explored. Because conventional aggregate supplies are ample at the present time in many areas, use of wastes and byproducts must be justified for each case on both an economic and an energy basis.

Quarry byproducts offer a large potential at a relatively low cost and low energy requirement. The quality of all waste and byproduct materials must be optimized with their end use in mind. This may require adjustments in material and construction specifications.

Development of a portable guardrail straightener would be of value to highway agencies. This device should be capable of being towed to the site requiring repair.

CONCLUSIONS

Based on the information presented in this synthesis, the following conclusions are warranted:

1. Pavement recycling and the use of waste materials and byproducts from industry, as well as the highway, afford the opportunity to reduce the aggregate supply problem in selected areas.
2. Costs for heater-planing and heater-scarification are on the order of \$0.20 to \$0.60/yd^2 (\$0.24 to \$0.72/m^2) for ¾-in. (19-mm) removal. Energy consumption of these devices is about 10,000 to 20,000 Btu/yd^2 (12 600 to 25 200 kJ/m^2).
3. Hot-milling operations are used to a limited extent in the eastern United States. Costs for this operation are approximately \$0.80/yd^2-in. (\$0.38/m^2-cm). Energy consumption is about 10,000 Btu/yd^2-in. (5000 kJ/m^2-cm).
4. Cold-milling operations have become popular in the last few years. Costs for these operations are approximately \$0.40 to \$0.80/yd^2-in. (\$0.19 to \$0.38/m^2-cm). Energy consumption is between 1,000 and 2,000 Btu/yd^2-in. (500 and 1000 kJ/m^2-cm).
5. In-place recycling operations have been practiced for a number of years. Specialized pulverization equipment is now available from a number of manufacturers to achieve more complete pulverization. Costs for in-place pulverization and restabilization are on the order of \$0.30 to \$0.50/yd^2-in. (\$0.14 to \$0.24/m^2-cm).
6. Central-plant operations that crush portland cement concrete and asphaltic concrete pavements exist in several large metropolitan areas of the United States. They use recycled materials primarily for unstabilized base courses.
7. Portland cement concrete pavement can be recycled into econocrete and portland cement concrete surface courses.
8. Hot central-plant recycling of asphaltic concrete has been accomplished without air pollution by several processes utilizing both direct and indirect heating of the crushed asphaltic concrete. Modifications of conventional batch and drum-mixer plants, as used on experimental projects, have experienced some air quality problems at high production rates.
9. Guardrails and sign blanks are presently recycled by state highway departments in significant amounts. Sign posts, delineator posts, and culverts are recycled in several states.
10. Significant quantities of fly ash, slag, and mining wastes are presently recycled by states. A wide variety of other materials has been used on an experimental basis by states, counties, and cities.

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APPENDIX A

PARTIAL LIST OF RECYCLING EQUIPMENT MANUFACTURERS AND CONTRACTORS

TABLE A-1

TYPES OF BUSINESS, EQUIPMENT, AND EXPERIENCE

Name of Company	Type of Business		Type of Equipment and/or Contracting Experience					
			Surface				Central	
	Equipment Manufacturer or Distributor	Contractor	Heater-Planer	Heater-Scarifier	Mill or Grind	In-place	Cold	Hot
Ajax Paving Industries	X	X	X	X	X			
American Asphalt Paving Co.		X	X	X				
Asphalt Equipment, Inc.	X	X	X	X				
Asphalt Milling Wirtgen Corp.	X	X		X				
Asphalt Treatment Corporation		X	X	X				
Babbler Brothers		X						X
Barber-Greene Co.	X							X
Barco Manufacturing Co.	X	X			X			
Bell and Flynn, Inc.		X				X		
Boeing Construction Equipment Co.	X							X
British Jeffrey-Diamond Limited	X				X			
BROS	X					X		
Chapin & Chapin, Inc.		X			X			
CMI Corporation	X				X			
J. C. Compton Company		X						X
Copp Paving		X					X	
Cutler Recycling, Inc.	X	X	X	X	X			
Eisenhour Construction Company, Inc.		X			X			
Everds Brothers, Inc.		X						X
L. G. Everist		X					X	
Excavation Construction, Inc.		X					X	
Fox Construction, Inc.		X					X	
Freestate Equipment Company	X	X			X			
Galion Manufacturing Division	X				X			
Gomaco	X					X		
Gilvin-Terrill, Inc.		X						X
Greenside Machine Company Limited	X				X			
Independent Construction Co.	X	X				X		
Iowa Manufacturing Co.	X							X
Jim Jackson Contractor	X	X	X	X				
Jarbet Company		X						X
I. F. Jensen		X					X	
Johnson Roadbuilder	X	X	X	X				
Kassler Corporation		X					X	
Peter Kiewit & Sons		X						X
Koehring	X					X		
Las Vegas Paving Corporation		X						X
McCrossan Paving		X						X
Merrimack Paving Corp.		X	X	X				
Midland Machinery Co.	X					X		
Midwest Asphalt	X	X				X		
Millars Machinery Company Limited	X				X			
J. Lee Milligan, Inc.		X	X	X				
Motheral Construction Company		X						X
New Haven Trap Rock/Tomasso, Inc.		X				X		
Ondrick Industries		X					X	
G. L. Payne	X	X	X	X				
James Peterson Sons, Inc.		X				X		
Pettibone	X					X		
Reclaimed Aggregate Company		X					X	
Reconoco, Inc.	X	X			X			
Rohlin Construction Company, Inc.		X						X
Roller & Roller, Inc.		X			X			
Sakai American, Inc.	X				X			
D. C. Speer Construction Co.		X						X
J. H. Strain & Son		X						X
Sully-Miller Contractor Co.		X					X	
Therma-Bond Asphalt Co.		X	X	X				
Vernon Paving Co.		X	X	X			X	
Warren Brothers	X							X

NAMES AND ADDRESSES

Ajax Paving Industries, Inc.
One Ajax Drive
Madison Heights, Michigan 48071
313-398-2300

American Asphalt Paving Company
750 East 120th Street
Chicago, Illinois 60628
312-821-1166

Angelo Benedetti, Inc.
Bedford, Ohio

Asphalt Equipment Company
P.O. Box 6486
Albuquerque, New Mexico 87107
505-344-7544

Asphalt Milling Wirtgen Corp.
343 Broad Avenue
P.O. Box 473
Ridgefield, New Jersey 07657
201-945-7200

Asphalt Treatment Corp.
1340 Powell Street
Emeryville, California 94603
415-658-6707

Babbler Brothers, Inc.
P.O. Box 02008
Portland, Oregon 97202
503-233-5536

Barber-Greene Company
400 N. Highland Avenue
Aurora, Illinois 60507
312-859-2200

Barco Manufacturing Co.
4522 Enterprise Place
P.O. Box 82841
Oklahoma City, Oklahoma 73108
405-943-2426

Bell & Flynn, Inc.
Stratham, New Hampshire 03885
603-778-8511

Boeing Construction Equipment Co.
P.O. Box 3707
Seattle, Washington 98124
206-773-0470

British Jeffrey-Diamond Limited
Construction Equipment Division
Thornes Works, Wakefield, WF2 8PT
Yorkshire, England

BROS
American Hoist & Derreck Company
63 South Robert Street
St. Paul, Minnesota 55107

Chapin & Chapin, Inc.
P.O. Box 568
Norwalk, Ohio 44857
419-668-8174

CMI Corporation
P.O. Box 1985
Oklahoma City, Oklahoma 73101
405-787-6020

J. C. Compton
P.O. Box 86
McMinnville, Oregon 97128
503-472-4155

Cutler Recycling, Inc.
P.O. Box 3246
Lawrence, Kansas 66044
913-843-1524

Duininck Brothers & Gilchrist
Prinsburg, Minnesota 56281
612-978-6011

Eisenhour Construction Company, Inc.
East Lansing, Michigan

Everds Brothers, Inc.
P.O. Box 520
Algona, Iowa 50511
515-295-7233

L. G. Everist, Inc.
P.O. Box 829
Sioux Falls, South Dakota 57102

Fox Construction, Inc.
4830 Holiday Drive
Madison, Wisconsin 53711
608-271-9101

Freestate Equipment Company
Sakai Heavy-Industries, Ltd.
2807 Sisson Street
Baltimore, Maryland 21233
301-889-7600

Galion Manufacturing Division
Dresser Industries, Inc.
Galion, Ohio 44833
419-468-4321

Gilven-Terrill, Inc.
P.O. Box 9027
Amarillo, Texas 79105
806-374-0932

Gomaco
Ida Grove, Iowa 51445

Greenside Machine Company, Ltd.
P.O. Box 19
Aycliffe Industrial Estate
Darlington, Co.
Durham, England

Gurries Company
884 Freeport Boulevard
Sparks, Nevada 89431
702-331-1550

Independent Construction Co.
740 Julie Ann Way
Oakland, California 94621
415-638-6375

Iowa Manufacturing Co.
916 16th Street, N.E.
Cedar Rapids, Iowa 52402
319-363-3511

Jim Jackson—Contractor
P.O. Box 988
Little Rock, Arkansas 72203
501-758-9704

The Jarbet Company
P.O. Box 606
San Antonio, Texas 78293
512-732-7811

I. F. Jenson Company
P.O. Box 1618
Sioux City, Iowa 51102
712-252-1891

Johnson Road Builders
International Sales & Contracting Office
27 Cortland Avenue
Toronto, Ontario, Canada
416-487-4527

Peter Kiewit & Sons
P.O. Box 748
Arcadia, California 91006

Koehring (U.S.A.)
Bomag Division
P.O. Box 959
Springfield, Ohio 45501
513-325-8733

Las Vegas Paving Corporation
1770 Industrial Road
Las Vegas, Nevada 89102
702-384-9040

C. S. McCrossan, Inc.
P.O. Box AD
Osseo, Minnesota 55369
612-425-4167

Merrimack Paving Corporation
Groveland, Massachusetts 01384
617-374-7600

Midland Machinery Co., Inc.
101 Cranbrook Ext.
Tonawanda, New York 14150
716-692-1200

Midwest Asphalt Paving Co.
1300 Souter Boulevard
Troy, Michigan 48084
313-588-6555

Millars Machinery Company Limited
P.O. Box 3, Bishop's Stortford
Herts., CM23 3JZ, England
0279 53134

J. Lee Milligan, Inc.
P.O. Box 4227
Amarillo, Texas 79105
806-373-4386

Motheral Contractors, Inc.
P.O. Box 476
Weslaco, Texas 78596

New Haven Trap Rock/Tomasso, Inc.
P.O. Box 76
Hamden, Connecticut 06518
203-288-8431

Ondrick Industries
Chicopee, Massachusetts 01014

G. L. Payne
P.O. Box 4906
Carson, California 90745
213-327-4060

Pettibone
Texas Corporation
P.O. Box 4249
Fort Worth, Texas 76106
817-232-1050

Reconeco, Inc.
P.O. Box 127
Greenville, South Carolina 29602
803-244-9760

Rohlin Construction Co., Inc.
1814 Seventh Avenue
Esterville, Iowa 51334
712-362-3549

Roller & Roller, Inc.
P.O. Box 32396
Oklahoma City, Oklahoma 73132
405-721-8970

Sakai American, Inc.
Suite 209
Baynard Building, Concord Plaza
3411 Silverside Road
Wilmington, Delaware 19810

J. H. Strain & Sons, Inc.
P.O. Box 277
Tye, Texas 79563
915-692-0067

Sully-Miller Contracting Co.
3000 E. South Street
Long Beach, California 90805
213-979-1873

Therma Bond Asphalt Co.
500 Bragato Road
Belmont, California 94002
415-592-4154

Vernon Paving Company
P.O. Box 489
Cerritos, California 90701
213-771-3677

Warren Brothers Company
675 Massachusetts Avenue
Cambridge, Massachusetts 02139
617-354-3300

APPENDIX B

PARTIAL LIST OF MODIFIERS FOR RECYCLING ASPHALT-AGGREGATE MIXTURES

TABLE B-1

COMPANY, PRODUCT, AND HISTORY OF USE

Petroleum or Oil Company	Product Name or Identification	History of Use: Laboratory Study	History of Use: Field Study
Arizona Refining Co.		x	
Ashland Petroleum Co.	Light Aromatic Oil	x	
	Medium Aromatic Oil	x	
	Slurry Oil	x	
	Ashland Plasticizer Oil (APO)	x	x
Bituminous Materials Company, Inc.		x	
Cenex	Dust Oil	x	
Chem-Crete Corporation		x	
Chevron USA, Inc.	Chevron X109	x	
	Chevron X90	x	
Mike Davis Associates		x	
Koppers Co., Inc.	BPR	x	x
Lion Oil Co.	Smackover Flux Asphalt	x	
	Rejuvenator Oil	x	
Mac Millan		x	
Mobil Oil Corp.	XMTY-125B	x	
	Mobilsol 30	x	
Pax International	Paxole	x	x
Phillips Petroleum Company	10 Extract	x	
	20 Extract	x	
	250 Extract	x	
Saunders Petroleum Company	SA-1	x	x
Shell Oil Co.	Dutrex	x	x
Sun Oil Co.	Sundex 840T	x	
	Sundex 790T	x	
Tenneco		x	
Union Oil Co.	Rejuv-Acote-Base	x	
Witco Chemical	Reclamite	x	x
	One-Component System	x	x
	Cutback Asphalt		x
	Emulsified Asphalt	x	x
	Califlux GP	x	
Numerous Companies	Soft Asphalt Cement	x	x
	Reclaimed Oil	x	

NAMES AND ADDRESSES

Arizona Refining Company
P.O. Box 1453
Phoenix, Arizona 85001
602-258-4843

Ashland Petroleum Company
P.O. Box 391
Ashland, Kentucky 41101
606-739-4166

Bituminous Materials Co., Inc.
P.O. Box 1507
Terre Haute, Indiana 47808

Chem-Crete Corporation
2180 Sand Hill Road
Suite 340
Menlo Park, California 94025
415-854-6206

Chevron USA, Inc.
P.O. Box 7643
San Francisco, California 94120

Koppers Company, Inc.
2700 Koppers Building
Pittsburgh, Pennsylvania 15219
412-391-3300

Lion Oil Company
Lion Oil Building
El Dorado, Arkansas 71730
501-863-3111

Mobil Oil Corporation
150 E. 42nd Street
New York, New York 10017

Pax International
W. 3815 Indian Trail Road
Spokane, Washington 99208
509-326-5989

Phillips Petroleum Company
Bartlesville, Oklahoma 74004
918-661-6600

Saunders Chemical Division
P.O. Box 9
Evans, Colorado 80620
303-352-0467

Shell Oil Company
P.O. Box 2105
One Shell Plaza
Houston, Texas 77001

Sun Oil Company
907 S. Detroit Avenue
Tulsa, Oklahoma 74120

Tenneco
1433 West Loop South
Houston, Texas 77027

Union Oil Company
P.O. Box 7600
Los Angeles, California 90051
714-528-7201

Witco Chemical Company
Golden Bear Division
P.O. Box 378
Bakersfield, California 93308
805-399-9501

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