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USE OF RECYCLED MATERIALS IN AIRFIELD PAVEMENTS FEASIBILITY STUDY

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AIR FORCE CIVIL ENGINEERING CENTER
(AIR FORCE SYSTEMS COMMAND)
TYNDALL AIR FORCE BASE
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This report describes an investigation of the economic and technical feasibility of recycling old pavements and used paving materials into new pavement construction and maintenance. It is in effect a state-of-the-art study based on literature reviews and job site visits. Four major procedures were identified as being used to recycle or reclaim pavements and paving materials. These are: (1) removed and crushed materials, (2) removed and reprocessed materials, (3) pulverized in-place, and (4) heater-planer scarifier or remix methods. It is concluded that pavement materials are recyclable and that

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recycling is beneficial in reducing consumption of high quality construction materials, in reducing energy requirements for paving operations, and impacts favorably on the environment by reducing the need for large waste disposal areas. Recommendations for future investigation and research are included.

PREFACE

This report documents work accomplished between October 1974 and August 1975 by the U.S. Army Engineer Waterways Experiment Station under Project Order No. 75-140 with the Air Force Civil Engineering Center, Tyndall Air Force Base, Florida. Lt Col George D. Ballentine was project engineer for the Civil Engineering Center.

This report has been reviewed by the Information Officer (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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INTRODUCTION

Construction and maintenance of pavements until now have been accomplished almost exclusively by using virgin-select materials. While the total resource of select materials throughout the United States seemed adequate for many years, several areas, especially major urban areas, are experiencing severe conventional aggregate shortages. In addition to scarcity of virgin materials, unreasonably high costs associated with transporting such materials over long distances have caused engineers to look to other materials and ways of solving the aggregate scarcity problems. Similarly, the price and availability of high-quality binders such as asphalt have been dramatically affected by the continuing energy crisis.

The problem of finding suitable virgin materials for pavements exists concurrently with the problem of disposal of solid wastes. Both of these problems are most apparent in our major population centers. Some of the materials considered to be solid wastes have properties similar to and may be substituted for virgin materials in pavement construction and maintenance. One large volume of solid waste material with good potential use for pavements is old pavements themselves. Using recycled solid waste materials in pavement construction and maintenance will help solve both the problem of material shortages and solid waste disposal.

The overall long-range objective of this research effort is to provide the Air Force civil engineer with acceptable criteria, specifications, and construction procedures for use of recycled materials in pavement construction and maintenance, while reducing the solid waste management problem. The scope of this study is to investigate the economic and technical feasibility of recycling old pavements and used paving materials into new pavement construction and maintenance and in effect is a state-of-the-art evaluation of recycling old pavements as related to Air Force needs.

To satisfy the long-range objectives, recommended continuation studies of materials and applications identified in this report will include laboratory evaluation and validation testing programs, development of design and construction criteria, and construction and observation of controlled prototype test sections at designated Air Force bases. Also, any new concepts of using solid wastes for paving will be evaluated.

Prior studies have investigated the status of conventional aggregate supplies as well as capability of the aggregate suppliers to meet demands of highway and building construction industries. In 1970 approximately 1.8 billion tons of conventional aggregates (i.e., crushed stone, sand,

and gravel) were produced. During 1975, total production of conventional aggregate will exceed 2.5 billion tons, and by 1985 production will approach 4.0 billion tons. Although this production on a national basis is sufficient to meet current and anticipated demands, certain areas of the United States are now, or soon will be, suffering critical shortages of conventional virgin aggregates. This situation is compounded in major urban areas because of zoning restrictions, environmental regulations, and appreciating land values.

The determination of which Air Force bases are located in present or potential aggregate shortage areas can be made from a National Cooperative Highway Research Program report by R.H. Miller and Robert J. Collins (Reference 1). They used an assumed economical haul distance of 40 miles and locations of crushed-stone quarries and sand and gravel pits in the United States from a report by Witzcak (Reference 2) to delineate areas of potential aggregate shortages. Locations of major Air Force bases and potential crushed-stone shortage areas are shown by the crosshatched area in Figure 1. Similarly, potential sand and gravel shortage areas are shown by the crosshatched area in Figure 2. All areas located farther than 40 miles from any source of natural mineral aggregate are shown by the crosshatched area in Figure 3. Figures 1, 2, and 3 indicate only those areas where the need for conventional aggregate would involve expensive hauling costs. Even within the areas indicated to have satisfactory aggregate supplies, demand for sizable quantities of aggregates could potentially result in aggregate shortages.

To verify locations where shortages of conventional aggregates now occur, Miller conducted a survey of all state highway materials engineers. Results of this survey are shown in Figure 4. All crosshatched areas shown are those noted by state highway materials engineers to be deficient in high-quality natural aggregate.

In addition to the areas shown in Figures 1 through 4, all major metropolitan areas must be considered to be experiencing some shortages in aggregates whether or not they have been shown.

References:

1. Miller, R.H. and Collins, R.J., "Waste Materials as Potential Replacements for Highway Aggregates," NCHRP Project No. 4-10A, Highway Research Board.

2. Witczak, Mathew W., Lovell, C.W., Jr., and Yoder, E.J., "A Generalized Investigation of the Potential Availability of Aggregate by Regional Geomorphic Units within the Conterminous Forty-Eight States," Highway Research Record No. 353, pp. 31-42.

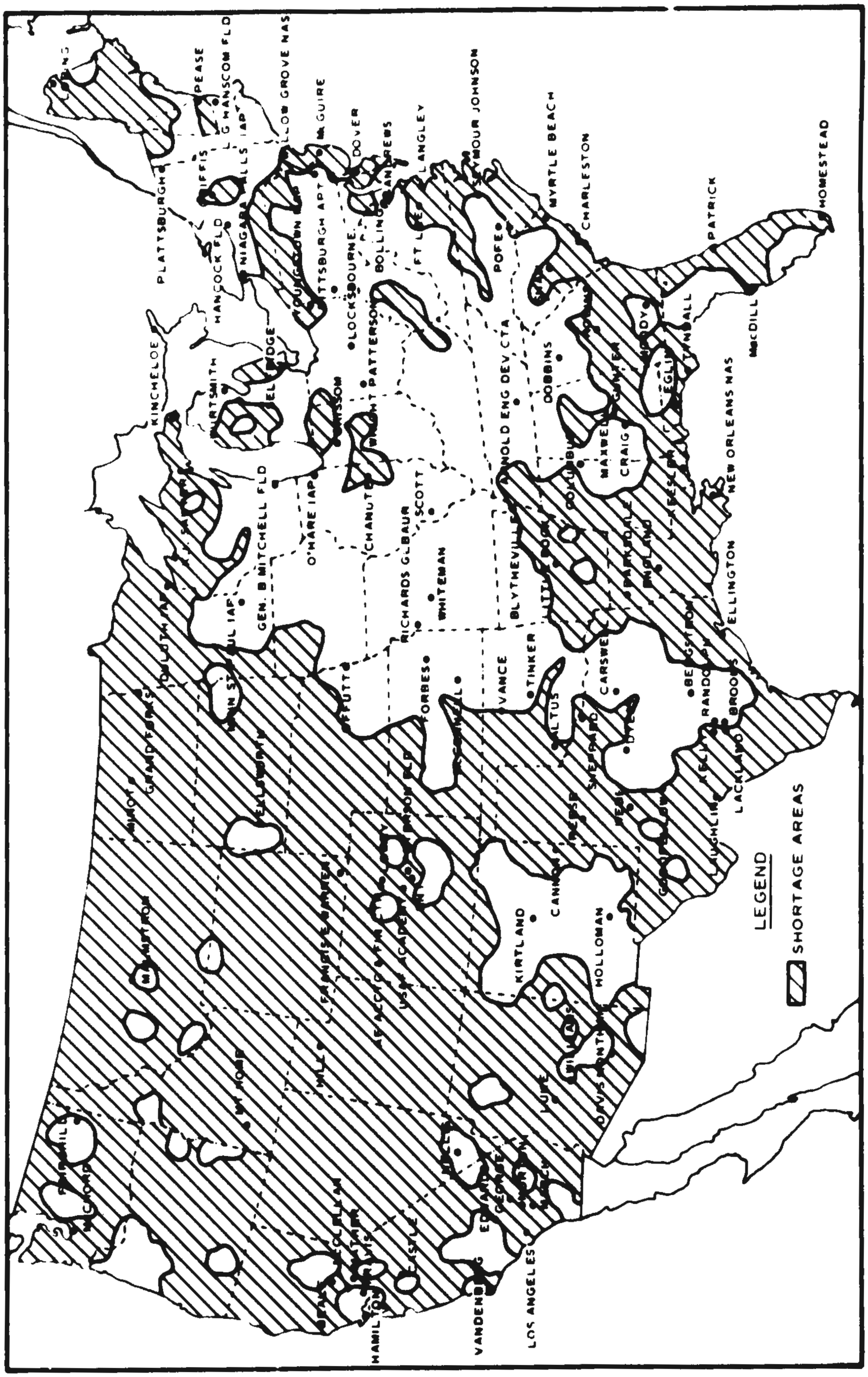

Figure 1. Crushed Stone Shortage Areas

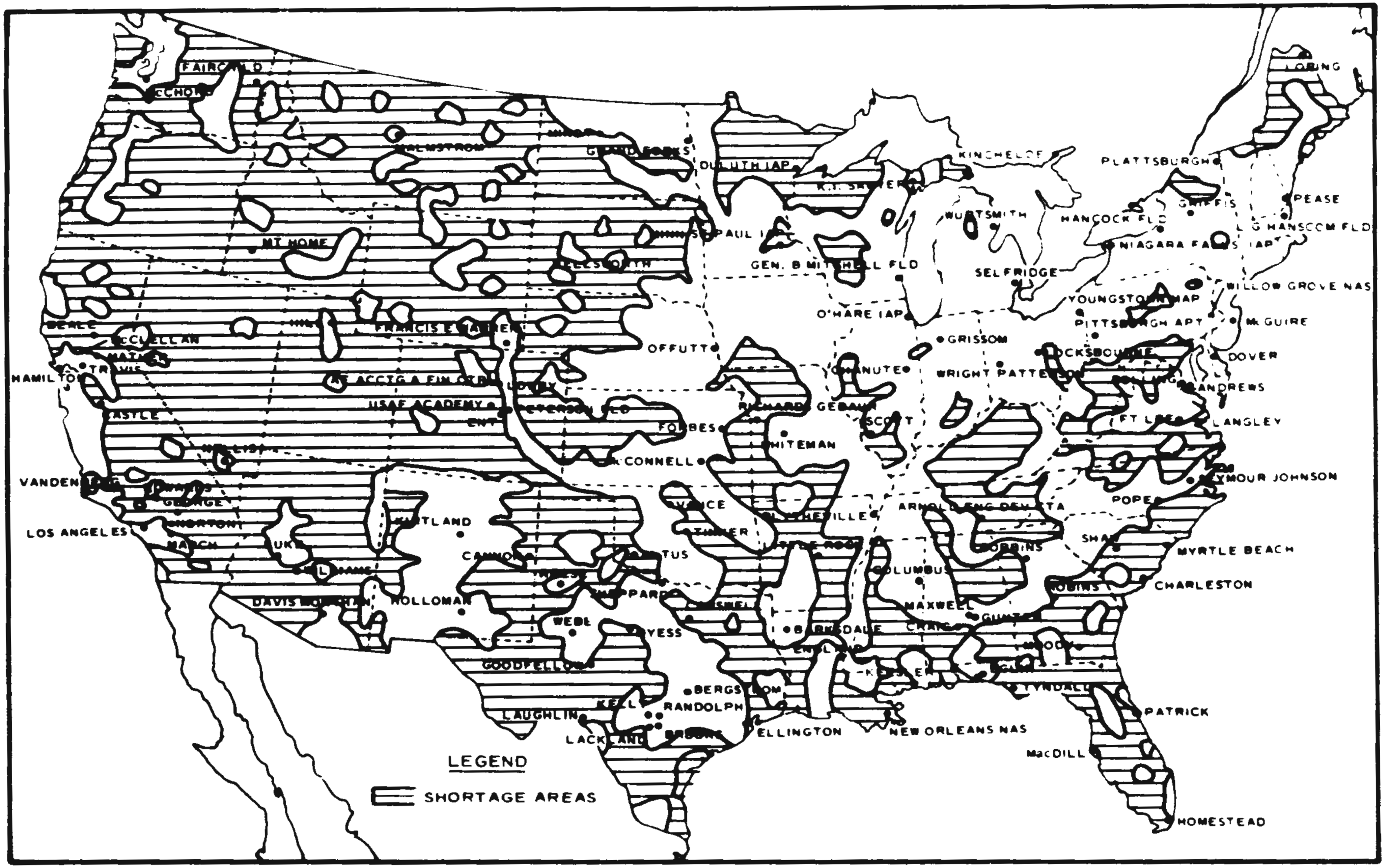

Figure 2. Sand and Gravel Shortage Areas

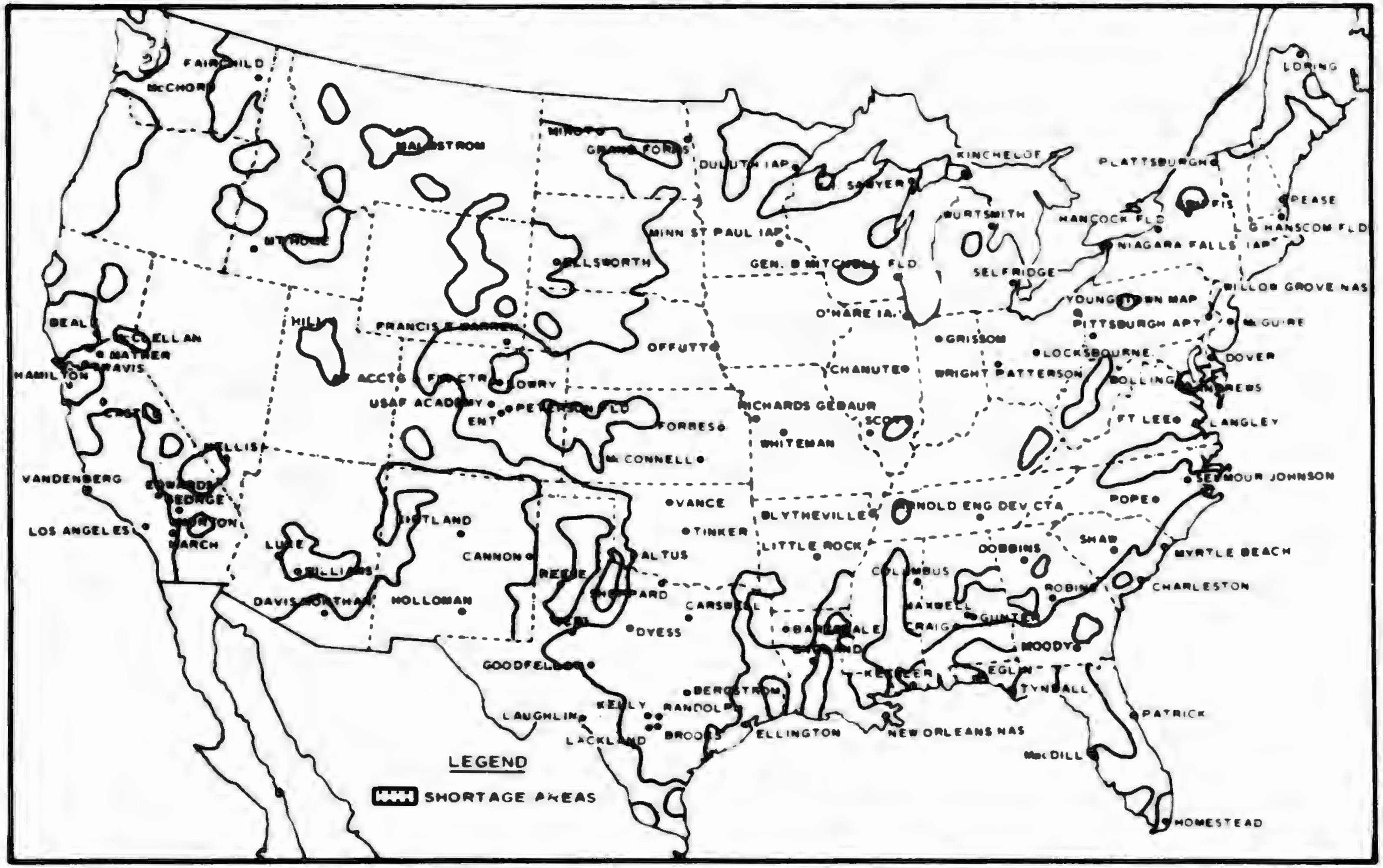

Figure 3. Aggregate Shortage Areas

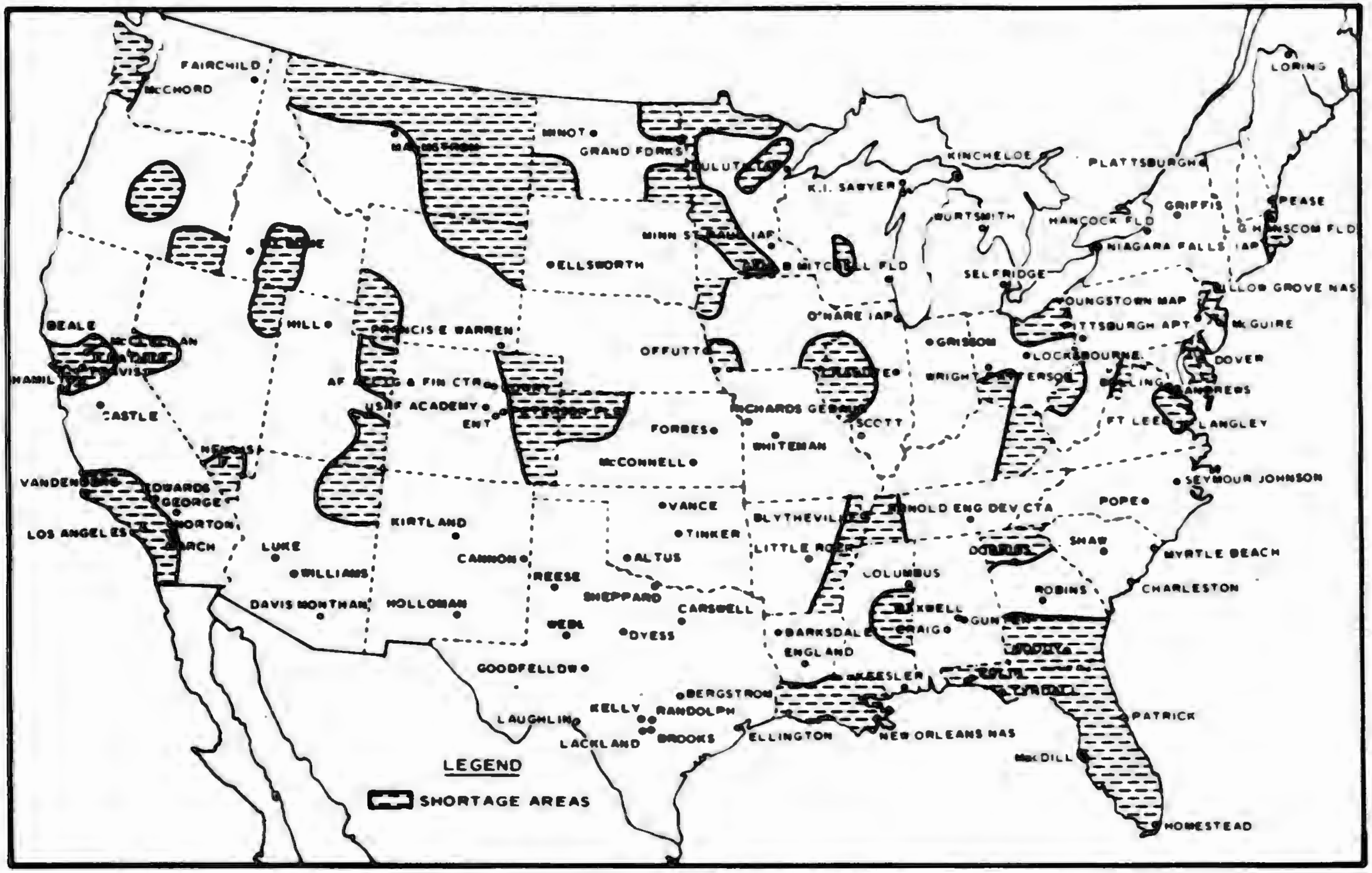

Figure 4. State Highway Departments Reported Aggregate Shortage Areas

The potential of using solid wastes to solve the aggregate shortage problem has real value when it is considered that approximately 3.5 billion tons of solid wastes are being generated annually. Utilization of waste materials in pavements would eliminate a significant volume of waste and, in turn, assign to it a commercial, marketable value. The use of these materials would also lessen the impact on our environment.

In their report, Miller and Collins (Reference 1) conducted a detailed technical, economic, and environmental evaluation of 31 waste materials as potential replacements for highway aggregates. Based on these evaluations, the waste materials most highly recommended for continued development as aggregate substitutes were blast furnace slag, fly ash, bottom ash, boiler slag, reclaimed paving material, and anthracite coal waste. The remainder of this report will deal specifically with the use of reclaimed paving materials.

There are currently four major procedures being used to recycle or reclaim pavements and paving materials. These are: (1) remove and crush, (2) remove and reprocess, (3) pulverize in-place, and (4) heater-planer. (There are two other processes, grinding and rejuvenation; however, these will not be covered in detail in this report). The first two procedures require complete removal of the existing pavement, while the latter two are process-in-place procedures. Technical, economic, and environmental aspects of these major processes will be presented in the following discussion. Information regarding each process was obtained from an extensive literature search and through personal contacts with companies currently using these processes and with former clients of companies marketing these processes.

SECTION II

REMOVE AND CRUSH RECYCLING PROCEDURE

The procedure of removing pavements and crushing them for use as base course materials has been fully developed over the past decade. Its application has increased rapidly, especially in major urban areas where good base materials have become relatively scarce and expensive and disposal of large amounts of rubble has become an economic and environmental problem. By crushing portland cement concrete, asphaltic concrete, and other construction materials, a high-quality base material can be produced, and the problem of rubble disposal reduced substantially.

a. Process

The basic process is shown by the flow chart in Figure 5. The first step involves preparing the pavement by cutting the outboard edges of the construction limits. The pavement is then ripped or scarified and broken into pieces with a maximum size of 3 to 4 feet. The broken pavement, along with a certain amount of existing base material, is hauled to the crushing plant. The material is crushed and sized to the required specifications and reused immediately or stockpiled for future use.

b. Equipment

All equipment used in this process is of the standard road building type. Motorgraders with scarifiers or bulldozers with ripper teeth are used to rip up the pavement. Heavy equipment, such as bulldozers, rollers, and compactors, is used if further breakdown is required. Front-end loaders and dump trucks are used for loading and hauling the material to the crushing plant. The crushing plants are either portable and located near the actual job site or in a stockpile yard or stationary and located in an existing pit or quarry. The portable crushing plants usually consist of a primary jaw crusher, which breaks the material down to about a 3-inch maximum, and a secondary cone crusher, which breaks the material down to the required maximum size (1-1/2 to 2 inches). Vibrating feeds and screens size the crushed material. Various conveyor belts and mobile equipment are used to handle the material and build stockpiles. Figure 6 shows a typical portable crushing plant. Production rates of these portable crushing plants vary from 100 to 350 tons per hour. Conventional spreaders and compactors are used to place and compact these materials.

There are problems associated with recycling paving materials through a portable crushing plant other than the usual ones of maintenance and dust control encountered in any crushing operation. Production rates will vary considerably depending upon the type and quality of material

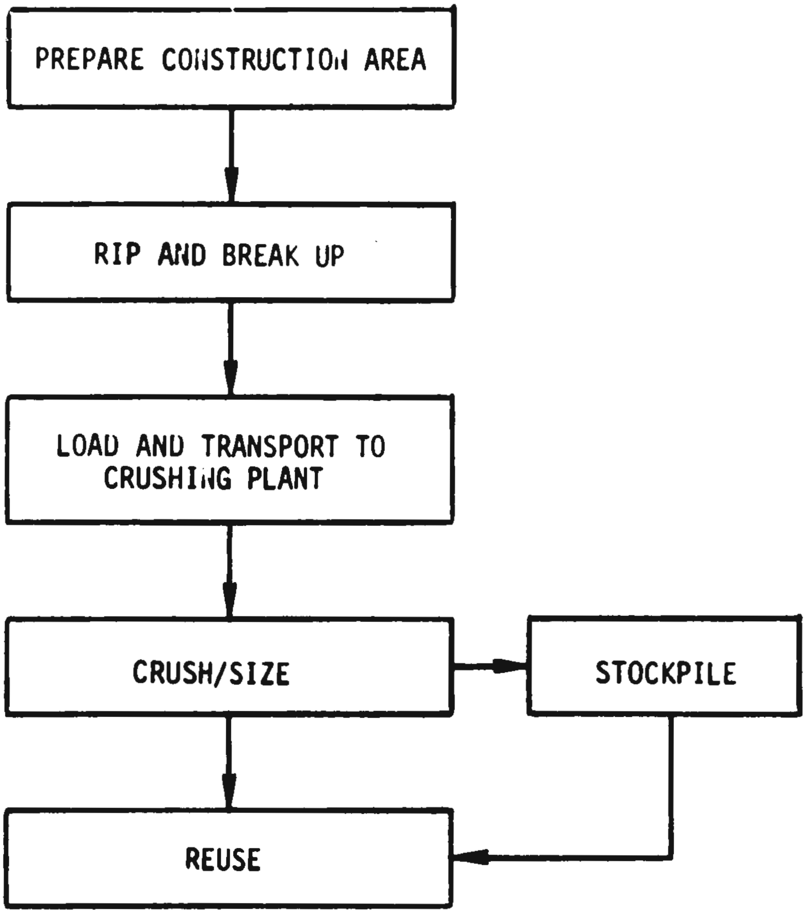

Figure 5. Process Flow Chart - Remove and Crush

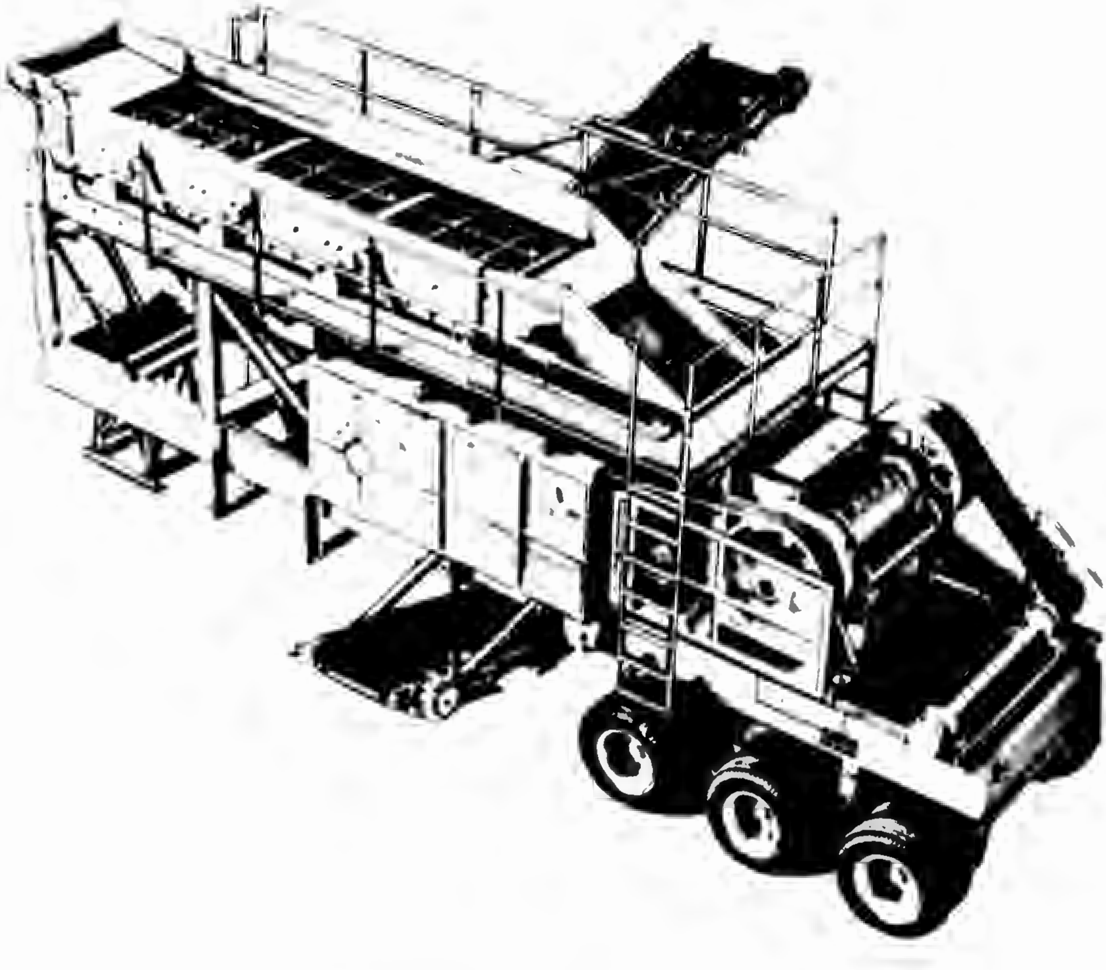

Figure 6. Portable Crushing Plant

supplied. Steel rebars, dowels, and wire mesh in recycled concrete pavements cause excessive wear in the crusher and may even jam the system. An excess amount of soft asphalt or dirt in the recycled material being crushed can gum up the crusher, drastically reducing production. Careful selection of materials to be processed will help minimize these problems. Use of water spray bars will generally solve the dust problem encountered when crushing old portland cement concrete.

c. Technical Aspects

Materials used in the past to produce recycled base courses have been an indiscriminate mix of oil, dirt, asphalt, clay, rock, concrete, and whatever existed on the job site. Despite being composed of a wide variety of materials, these crushed products have been processed to a good degree of homogeneity, and their compaction characteristics have often been better than those of conventional base course, requiring less effort to compact and obtain grade. One benefit of using recycled materials is that the unhydrated cement in recycled concrete and the asphalt in recycled asphalt concrete form excellent binders.

Use of recycled paving materials for construction of base course layers is rapidly increasing, especially in major urban areas. In Los Angeles County, where conventional aggregate is in short supply and disposal of demolition rubble is a problem, the Los Angeles County Road Department has incorporated specifications for the use of processed miscellaneous base (PMB) into their Standard for Public Works Construction. The PMB specification reads as follows:

> "200-2.4 Processed Miscellaneous Base. Processed miscellaneous base shall consist of broken railroad ballast, glass, crushed rock, rock dust, or natural material. The material that is retained on a No. 4 sieve shall contain no more than 75 percent gravel particles as defined in Subsection 200-1.3. The material shall be free of any detrimental quantity of deleterious materials as defined in Subsection 200-1.1.
>
> "200-2.4.1 Grading. The material shall be uniformly graded and shall conform to one of the following gradations:

PROCESSED MISCELLANEOUS BASE

Sieve Size	Percentage Passing Sieve Coarse	 Fine
2"	100	
1-1/2"	85-100	100
3/4"	55- 80	80-100
#4	27- 47	35- 60
#30		10- 30
#200	2- 11	2- 11
ASTM C-131 Test Grading	A	B

"When there is a difference in specific gravity (bulk saturated surface dry per ASTM C-127) of 0.2 or more between that portion retained and that portion passing a No. 4 sieve, the grading will be modified by Test Method No. California 905.

"200-2.4.2 Quality Requirements. This material shall conform to the following:

Tests	Test Method	Requirements
R-Value	Calif. 301	75 Min.
Sand Equivalent	Calif. 217	30 Min.
Percentage Wear	ASTM C-131	
100 revolutions		15 Max.
500 revolutions		52 Max.

1. The R-Value requirement will be waived, provided the material has an SE of 30 or more.

"The Engineer may waive the percentage wear requirements, provided the material has a minimum durability of 35 in accordance with Test Method No. California 229."

Of approximately 210,000 tons of aggregate base course placed in November 1974 on Los Angeles County highway projects, 50 percent was PMB.

One of the private companies currently producing PMB in Los Angeles County is Sully-Miller Contracting Company. Sully-Miller uses two portable crushing plants with capabilities of 135 to 245 tons per hour and seven strategically located recycling yards to produce and market recycled base material. They budgeted for the sale of approximately 350,000 tons of recycled material during 1975. Table 1 presents a summary of an independent laboratory report on a typical material produced by Sully-Miller to meet the standard specifications of the Los Angeles County Road Department for PMB.

TABLE 1. LABORATORY REPORT ON RECYCLED BASE
GRADATION AND SAND EQUIVALENCY

Sieve Size	Percent Passing	
	East	West
1-1/2 inch	100	
1 inch	99.3	100
3/4 inch	89.7	93.6
1/2 inch	73.2	77.0
3/8 inch	64.0	68.3
No. 4	45.4	50.5
No. 8	36.7	40.1
No. 16	29.6	30.7
No. 30	25.3	25.1
No. 50	19.8	18.4
No. 100	14.2	12.4
No. 200	9.8	9.0
Sand equivalency	39	39

Stabilometer Results - El Segundo

	No. 1	No. 2	No. 3
Dry density as compacted (psf)	125.0	124.0	122.3
Moisture content as compacted (percent)	5.0	6.0	7.0
Expansion pressure (dial reading x 10^4)	0	0	0
Exudation pressure (psi)	555	320	190
Stabilometer R value	86	86	86

R value equilibrium (300 psi exudation pressure) = 86

Classification: crushed asphalt and concrete particles

Specification limits: R value = 75 minimum

By: Advanced Foundation Engineering, Inc.

Another major urban area where the use of recycled materials for base course construction is increasing rapidly is the Washington, D.C., metropolitan area. As was the case in Los Angeles, a shortage of good quality aggregate and the ever-increasing problem of construction rubble disposal have enhanced recycling of usable materials. The District of Columbia has written a specification for the use of recycled materials for base courses. It is quoted as follows:

> "24. RECYCLED MATERIALS FOR BASE COURSE, Item 309 005
>
> Crushed recycled material may be used in lieu of soils base material as directed by the Engineer.
>
> "Materials of this type for use in base course shall meet the following specification and may be rejected on visual inspection pending the testing of samples.
>
> "The combined aggregate for this use shall consist of crushed concrete or mortar, crushed bituminous mixtures, crushed brick, crushed stone, and crushed or uncrushed sand and gravel. In addition, the combined aggregate may contain up to 10 percent by weight crushed glass or clean cinders. Materials that break up under alternate freezing and thawing or wetting and drying shall not be used.
>
> "Coarse aggregate retained on the No. 10 sieve shall have a percentage of wear of not more than 50.
>
> "The fraction passing the No. 200 sieve shall not be greater than two-thirds of the fraction passing the No. 40 sieve. The fraction passing the No. 40 sieve shall have a liquid limit not greater than 25 and a plasticity index not greater than 6.
>
> "The composite material shall be free from vegetable matter and lumps or balls of clay and shall conform to the following grading requirements:

Sieve Size	Total Percent Passing by Weight
2-1/2"	100
2"	90 - 100
3/4"	60 - 90
#4	30 - 60
#10	20 - 45
#40	10 - 30
#200	4 - 12

> "Compaction of the recycled material shall meet the requirements of soils base material per S.P. for DENSITY REQUIREMENTS.

> "Payment for recycled material including compaction will be per cubic yard. The number of cubic yards will be the actual volume of the recycled material of variable dimensions, measured complete in-place."

d. Economic Aspects

The economic advantages of using recycled paving materials are most evident in urban areas where good base materials are relatively scarce and expensive and where large volumes of rubble are available and hauling costs to disposal sites are very high. In the Los Angeles area, Sully-Miller estimates savings of $0.35 to $2.00 per ton in addition to reduced trucking costs when using recycled base in place of conventional aggregate base. To the additional savings for trucking costs can be added elimination of dumping fees, reduction in wear and tear on trucks, and reduced mileage and time required for conventional disposal. There is also some additional savings through the retention and use in the recycling process of the gravel base, which is usually hauled away with a broken up pavement. Overall, the Los Angeles County Road Department estimates costs of PMB at approximately $3.00 per ton, a savings of $2.00 to $3.00 per ton over conventional aggregate base.

e. Environmental Aspects

As the supply of conventional aggregates is consumed at an increasing rate, the use of recycled base will become more significant. The aggregate portion of old pavements can be reclaimed and used in recycled bases to help conserve the dwindling aggregate supply. By recycling these solid wastes, the natural landscape will be preserved, and the areas required for disposal of such wastes will be decreased. This will be especially beneficial in urban areas where disposal sites are already a critical problem. The use of recycled paving materials in the construction of base courses is an important alternative in helping preserve our environment.

SECTION III

REMOVE AND REPROCESS RECYCLING PROCEDURE

The remove and reprocess procedure has been developed over the past 6 years to address not only the problem of diminishing supplies of quality aggregate but also the problems of dramatically increased prices and limited supplies of asphaltic products caused by the energy crisis. Mr. Robert L. Mendenhall, President of Las Vegas (Nevada) Paving Company, has developed a prototype mixing plant through which old or discarded asphalt concrete may be recycled to produce hot-mix pavements. The mixing plant is called the RMI Thermomatic Plant and is a modified dryer drum designed to produce hot asphalt mixes using either virgin paving materials or recycled asphalt concrete. In the production of hot asphalt mixes using old asphalt concrete, the desired mix properties can be attained by addition of a softening agent, more asphalt cement, and aggregates either altogether or separately.

a. Process

The basic process is shown by the flow chart in Figure 7. The initial steps in this process are the same as those used for the remove and crush procedure. First, if required, the outboard edges of the construction limits are cut. The pavement is then ripped or scarified and broken into pieces small enough to be handled by end loaders. The broken pavement along with as little of the existing base as possible is hauled to the crushing plant. The material is crushed, sized, and stockpiled for future use or processed through the RMI Thermomatic plant. If necessary, after the old pavement is removed, the pavement subbase and base could be reworked and compacted. A prime coat is applied to the reworked base before the recycled hot-mix pavement is placed. After the recycled hot-mix is placed, final adjustments to manholes and other structures are made as the area is dressed up.

b. Equipment

All equipment used in this process except the RMI Thermomatic Plant is of the standard road building type. For instance, bulldozers with ripper teeth are used for initial pavement breakup. Heavy equipment, such as bulldozers, rollers and compactors, is used if further breakdown is required. Front-end loaders and dump trucks are used for loading and hauling the broken bituminous pavement to the crushing plant. The portable crushing plant presently being used consists of a 12- by 36-inch twin jaw and one double roller-crusher with various feeds and conveyors to move the material. Conventional equipment is also used for reworking and compacting the base course as well as placing and compacting the recycled bituminous hot-mix.

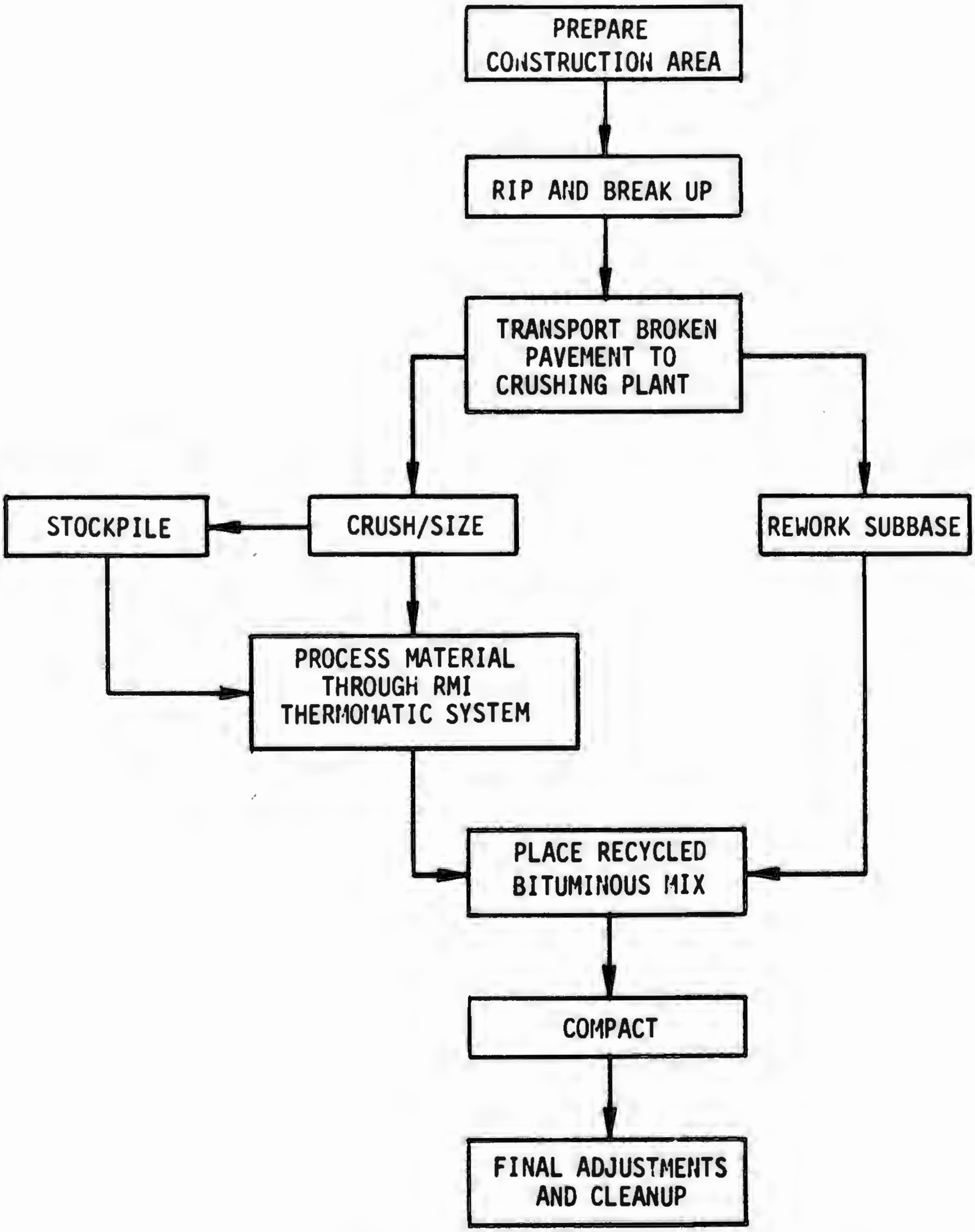

Figure 7. Process Flow Chart - Remove and Reprocess

Figure 8. Crushing Operation

Figure 9. Close-Up of Crushing Operation

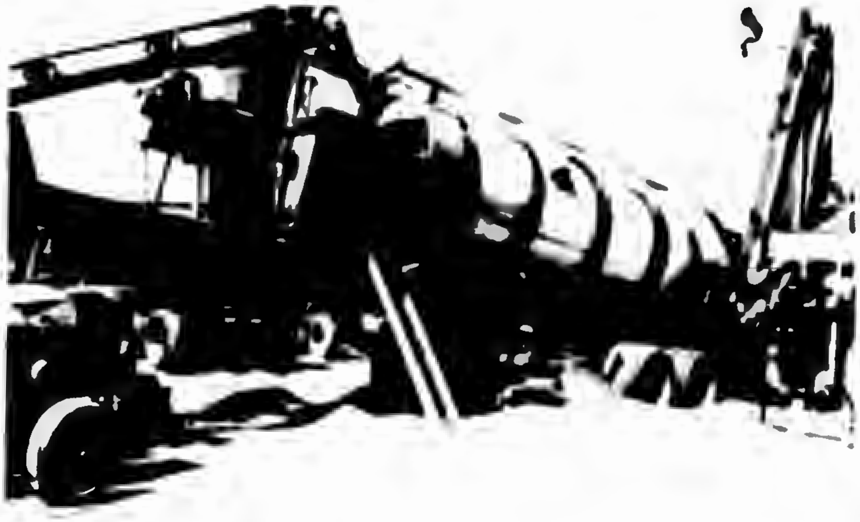

Figure 10. RMI Heat Exchanger

Figure 11. Intake End of Heat Exchanger

Figure 12. Burner Mounted at Right Angle to Heat Exchanger

Figure 13. Continuous Pugmill

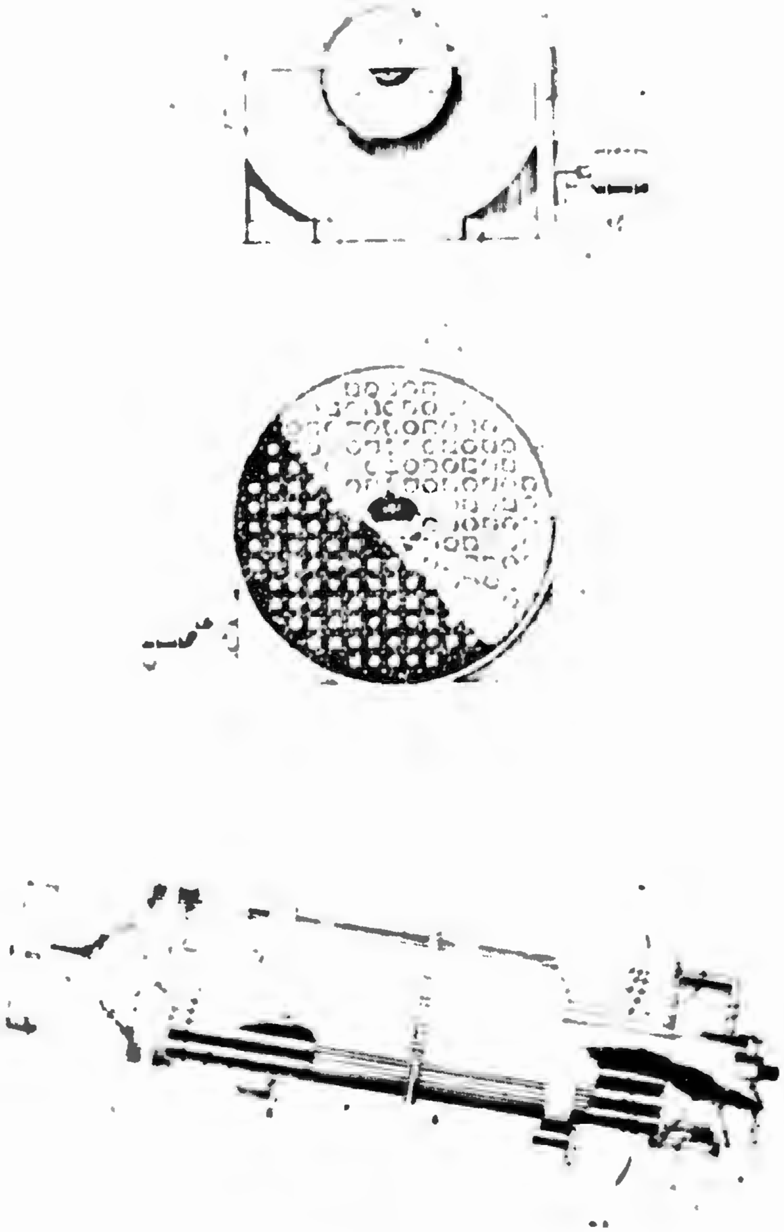

Figure 14. Schematics Showing Internal Components of Heat Exchanger (Taken from U.S. Patent)

The basic components of the prototype RMI Thermomatic Plant include screening devices for separating the crushed bituminous materials into sizes, cold bins, apron feeders for proportioning, heat exchanger for heating and drying the bituminous material, a continuous pugmill, storage tanks, and electrical generating plant for power. The plant is completely portable. Figures 8 through 13 show general views of the plant and its components.

As discussed above, modifications to recycled bituminous concrete materials can be made by new aggregates added proportionally at the cold bins. Additional asphalt of a chosen grade or an asphalt additive either separately or together may be added proportionally to the mix in the continuous pugmill.

The internal structure of the RMI heat exchanger alleviates the problem of combustion of bitumen in the recycled bituminous material. Figure 14 (taken from the U.S. Patent granted for the heat exchanger) shows the internal components of the heat exchanger. The exchanger consists of a modified dryer drum having a number of hollow tubes extending lengthwise of the drum with a combustion chamber in its lower end. In its present form the burner in the combustion chamber is mounted at right angles to the heat exchanger. Heat is drawn up through the hollow tubes (fire tubes) by a fan mounted near the intake end (upper end) of the drum. The crushed recycled bituminous mixture is introduced into the upper end of the drum, heated, further broken down and mixed by tumbling over the heated tubes as the drum is rotated, and withdrawn from the lower end of the drum. Moisture is vented from the drum by openings in the side and at the intake of the drum. Vapors from the mixing chamber are routed through the combustion chamber to reduce unburned hydrocarbons exhausted to the atmosphere.

c. Technical Aspects

Since this is a relatively new process, no long-term evaluation of its technical aspects has been conducted. An evaluation of some of the demonstration projects constructed with the 80 tons per hour prototype plant is included in this report. A larger production model with a rated capacity of 240 to 300 tons per hour is presently being built and will provide an opportunity for a more thorough technical and economic evaluation.

The opportunity to modify the recycled materials in this process is a distinct advantage. Indications are that existing evaluation and design procedures can be used to adopt the optimum modification scheme. For example, a proposed recyclable material can be evaluated in the laboratory by conducting extractions and gradations. The asphalt can be recovered and the asphalt properties determined. If it is determined that the asphalt properties require improvement, either or both additives and additional asphalt can be combined with the original recovered asphalt and the changes determined by testing (i.e., the viscosity of an asphalt can be reduced by additives down to an acceptable value for mixing and compaction). An evaluation of the gradation will indicate any deficiencies and proper aggregate sizes added. In any case, once desired asphalt properties and gradation are obtained, conventional mix designs (i.e., Hveem, Marshall) can be used to establish the final mix properties.

At this time, this recycling process has been used for producing paving mixture for private jobs in Las Vegas, such as the Showboat Hotel, Trinity Temple, Union Pacific Railroad yards, and various commercial parking lots. Test sections have also been constructed for the City of Henderson, Nevada, on a street reconstruction project in 1973; for Clark County, Nevada, at McCarran International Airport, Las Vegas, in July 1974; and for the Nevada Department of Highways on Interstate I-15 south of Las Vegas in October 1974.

The project on Interstate 15 was conducted in cooperation with the Federal Highway Administration (FHWA) to evaluate this process of recycling asphalt pavements. A one-mile section of the southbound lanes of Interstate 15 approximately 16 miles south of Las Vegas was chosen for the test. The original 4-inch asphalt concrete pavement was constructed in 1959 and had the proportions shown in Table 2.

TABLE 2. ORIGINAL ASPHALT CONCRETE PROPORTIONS, I-15, NEVADA

Gradation

Sieve Size	Percent Passing
3/4 inch	99.1
No. 4	57.3
No. 10	41.9
No. 40	23.2
No. 200	5.9

Asphalt Cement

5.3 percent	85-100 pen

At the time it was decided to recycle this pavement, the travel lane was suffering severe cracking, raveling, and dislodgment of pieces of pavement. While the passing lane was still in good condition, it was decided to recycle only the travel lane and outside shoulder. Plans called for the original 4-inch-thick travel lane to be recycled to a depth of 5-1/2 inches while the travel lane and outside shoulder were to be overlain with new materials. Future plans call for placement of a plant mix seal coat wearing surface.

Samples of the old pavement were obtained and analyzed. AR-8000 and Paxole 1009[1] were chosen as the asphalt and softening agent to be added to obtain the desired binder content and consistency in the recycled mix. Paxole 1009 is an aromatic oil with the properties shown in Table 3.

TABLE 3. PROPERTIES OF PAXOLE 1009

Flash point, COC (deg F)	390 min
Analine point, mixed (deg F)	75-99
Refractive index	1.599-1.630
Specific gravity	1.025-1.040
Viscosity at 210°F(CS)	17-25
Viscosity at 140°F(CS)	200-300

Three job mix designs were produced using different percentages of AR-8000 and Paxole 1009. Properties of these mix designs and a final modified job mix design which was used for the major portion of the project are shown in Table 4.

TABLE 4. SUMMARY OF MIX DESIGN, I-15, NEVADA

	Preliminary Mix Design Day 1	Day 2	Day 3	Modified Job Mix Design
Percent AR-8000 added (319-325^{0}F)	1.0	1.5	1.0	1.5
Percent Paxole added (190-200^{0}F)	0.5	0.5	0.75	0.75
Hveem R value	50	38	25	45
Percent air voids	7.4	6.8	6.5	6.8

The second day the percent AR-8000 added was increased because the mix appeared too dry and lifeless with little movement under the rollers. The third day the percent AR-8000 was reduced back to 1.0 and the percent Paxole 1009 was increased to evaluate the effect of additional Paxole. One factor suggested for the increase in binder content and Paxole for a satisfactory final mix design was the additional natural aggregate from the base course which was picked up with the broken pavement.

The recycled bituminous mixture was placed at temperatures between 245° to 260°F. It produced a smooth uniform surface comparable to asphalt concrete made with virgin materials. The laboratory maximum density of

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[1] Available from Pax International, 300 South Harbor, Suite 802, Anaheim,CA

the recycled mix was 138.7 pounds/cubic feet. Five core samples averaged 133.1 pounds/cubic feet or 96.0 percent compaction relative to the laboratory density.

Several problems were encountered during construction of this demonstration project. During the removal operation, almost 2 inches of base material was removed with the broken pavement. As pointed out above, this material probably contributed to the increased asphalt and Paxole 1009 needed in the final modified mix design. Removal of this base course material also resulted in a pavement thickness of 7-1/2 inches rather than 5-1/2 inches as had been planned. Also, as stated in Section II, crushing plants have a tendency to jam when fed with large chunks of soft bituminous materials. For this project, stockpile techniques for the crushed bituminous materials were poor, resulting in loss of material due to contamination with underlying soil. Finally, limited capacity (80 tons per hour) of the prototype plant coupled with numerous mechanical breakdowns prevented the paver from operating continuously, which reduced the general quality of the job.

d. Economic Aspects

A cost analysis of producing asphalt concrete with virgin-select material in the Thermomatic Plant conducted by RMI Systems shows a savings of about $0.27 per ton for an 800 TPD Thermomatic Plant and a savings of about $0.255 per ton for a 1600 TPD Thermomatic Plant when compared to a conventional pugmill type asphalt plant. These cost savings should be even greater using recycled paving materials, although the actual amount will depend on a given job.

To evaluate the potential savings which can be realized by recycling pavement in place of conventional methods for reconstruction, RMI Systems developed a cost comparison between the two methods for a recent project in Henderson, Nevada. The project consisted of removing 68,941 square yards of existing 2-inch asphalt concrete, reworking the base, and repaving with 2 inches of recycled asphalt concrete pavement. A savings of 23 percent was projected on the basis of the total project being accomplished with the RMI process. Details of the analysis are shown in Table 5. As part of this project, approximately 10,000 square feet of recycled asphalt concrete were placed as a demonstration.

Due to the limited production capacity of the prototype plant, the State of Nevada did not conduct an economic cost evaluation of the Interstate 15 recycling demonstration project. However, the Federal Highway Administration Demonstration Division and RMI Systems both conducted separate economic evaluations.

The FHWA used the actual production time and delays of less than

TABLE 5. COST COMPARISON BETWEEN CONVENTIONAL METHODS AND RECYCLING ASPHALT: CITY OF HENDERSON, NEVADA

CONVENTIONAL METHOD	PER TON	TOTAL
As bid	$7.50	$68,069.25
RMI THERMOMATIC SYSTEM	PER TON	TOTAL
Pulverizing existing material at dump site	$0.90	
Recycling and mixing	1.50	
Haul	0.80	
Laying	1.50	
Subtotal	$4.70	
Additional asphalt, 1/2 of 1%	0.18	(Asphalt Cement, $36.00 per ton, FOB Plant)
Softening agent, 0.90 of 1%	0.58	
Subtotal	$5.46	
Miscellaneous costs (used to equalize unit prices because they were included in the unit price for new asphaltic concrete)	0.32	
Total cost	$5.78	$52,458.70
Savings	$1.72	$15,610.55

NOTE: This project was constructed in October and November 1973 prior to the increases in petroleum products costs.

15 minutes to determine the rate of production and subsequent cost of production for the project. Delays lasting longer than 15 minutes were assumed to be caused by equipment breakdown and repair and/or administrative control of the project and therefore were excluded from the cost estimate. Labor costs were determined from prevailing rates in the area. Not included were plant rent, lease fee, or royalties to RMI. The contractor's overhead and profit were assumed at 15 and 20 percent, respectively. Details of the FHWA cost analyses are presented in a State of Nevada Department of Highways Report. A summary of this analysis is shown in Table 6.

TABLE 6. SUMMARY OF COST, I-15, NEVADA

Recycled Bituminous Surface	Estimated Cost/Ton
Scarification, loading, and hauling old asphaltic concrete to disposal area	$1.01
Refinishing subgrade	0.22
Pulverizing old asphaltic concrete	2.23
Recycling asphalt	2.06
Hauling	1.34
Laydown	1.97
Total projected contractor's unit cost for recycled bituminous surface	$8.83
Additional Cost for Binder and Additive	
Asphalt Cement, Grade AR-8000:	$1.24
Paxole 1009 (softening agent)	$1.19

Using bid tabulations for the Interstate 15 project, RMI Systems developed a longer term economic analysis to show the advantage of using their recycling system. The original plan specified by the Nevada Highway Department for the entire project length of 9.764 miles consisted of:

> Overlaying the existing surface with 1-inch-thick, 1/2-inch maximum aggregate, using SC3000 mixing oil. This was proposed with the idea that the slow curing oil might penetrate the cracks and heal the broken pavement.

Overlaying the above 1-inch layer with a 1-1/2-inch, 3/4-inch maximum-size aggregate, hot-mix using AR-8000 viscosity grade asphalt.

The wearing course would be a plant mix open-graded surface course on the traveled pavement lanes. The wearing surface for the shoulder would be a 3/4-inch surface treatment.

The bid was for material, labor, etc., but the asphalt binders (asphalt, cutback, and emulsion) were on a cost basis and paid at cost by the Highway Department.

Lowest bid price	$501,086.00
Asphalt binders	281,558.49
Total cost of project	$782,647.49

A life expectancy of 7 years was assumed with no appreciable maintenance. This cost yields:

$$\frac{\$782{,}674.49}{7 \text{ years} \times 9.764 \text{ miles} \times 2 \text{ lanes}} = \$5{,}725.66 \text{ per mile year.}$$

The recycling plan proposed by RMI consisted of recycling a 22-foot width consisting of the travel lane and shoulder and then capping the pavement with a plant mix open-graded surface course. The shoulder would receive a 3/4-inch surface treatment. Total cost using the RMI proposal was estimated to be $578,462.10 with an assumed life expectancy of 15 years. This yields:

$$\frac{\$578{,}462.19}{15 \text{ years} \times 9.764 \text{ miles} \times 2 \text{ lanes}} = \$1{,}974.81 \text{ per mile year.}$$

All the cost data presented for the RMI System of recycling have been developed from the operation of a small prototype plant or from information supplied by the system developer. More realistic cost figures will be available when a full-scale production plant is completed and in operation on larger projects. Nevertheless, the small amount of economic information developed thus far shows that the RMI System does have a high potential for economic benefit.

In addition to the straightforward savings in operating costs, there are other savings which are inherent in the use of recycled pavements. One savings is in the amount of fuel required to dry and heat the crushed bituminous concrete material. Laboratory tests conducted by RMI Systems show that asphalt pavement material being recycled usually contains no more than 3 percent moisture. The greatest savings in using recycled pavement, however, is the cost of raw materials. Not only is there a great savings through the reuse of the aggregate portion of the mix but also through reuse of the asphalt cement. For example, 1,000 tons of asphalt pavement contain approximately 285 barrels of asphalt and 950 tons of mineral aggregate. The price of aggregate has increased, but the increase in the price of asphalt is even more dramatic. It is projected that the continuing rise in price of these raw materials will offer a continuing increase in savings by recycling pavements.

e. Environmental Aspects

The potential for environmental benefit by using the RMI System to recycle old or discarded asphaltic concrete pavement is just as high as the economic benefit. As identified above, 1,000 tons of asphalt pavement contain approximately 285 barrels of asphalt and 950 tons of well-graded aggregate. Recycling of asphalt pavements not only conserves both these natural resources through reuse but also eliminates the necessity of locating disposal sites for the discarded pavements. The RMI System requires less energy than a conventional pugmill asphalt plant. This savings in energy when coupled with its ability to conserve natural resources by recycling old asphalt pavements makes the RMI System highly advantageous in helping preserve the environment.

SECTION IV

PULVERIZE IN-PLACE RECYCLING PROCEDURE

In-place processing of old asphalt and portland cement concrete pavements is not a new concept. A number of projects have been done utilizing conventional construction equipment, such as bulldozers, compactors, and rollers, to crush old pavement and combine it with a portion of the existing aggregate base to form a new stabilized base course. The residual asphalt and unhydrated cement in these old pavements acted as excellent binders in the new stabilized bases. Good quality bases were produced by in-place processing of both asphaltic concrete and some nonreinforced portland cement concrete pavements.

Current refinements of in-place processing techniques and equipment have been primarily in the development of pulverizing equipment and techniques using traveling hammermills for the recycling of asphaltic concrete. In-place processing of portland cement concrete is complicated by the presence of reinforcing steel. At this time, recycling of old reinforced portland cement concrete pavements is more efficiently accomplished by using the remove and crush procedure.

In-place processing offers the same economic and environmental advantages as the remove and crush procedure but eliminates the time and expense involved in transporting material to the crushing plant, crushing it, and returning it to the job site.

a. Process

The basic process is shown by the flow chart in Figure 15. The first step involves preparing the pavement by cutting the perimeter of the construction and lowering all structures (water and gas shutoffs, manholes, etc) to below the depth of pulverization. The pavement is then ripped or scarified and broken into pieces with a maximum size of 4 to 5 inches. The broken pavement is pulverized to the required specification and mixed with a predetermined amount of the existing aggregate base. If necessary, this mixture can be windrowed to the side so that the subbase can be reworked. An additional cementing agent, such as lime, cement, or asphalt, can be added, if desired, to assist in the stabilization process. The reclaimed mixture is then graded and compacted to form a stabilized base. A tack or prime coat, as required, is applied and a new wearing surface is placed over the recycled stabilized base. Finally, all structures are adjusted and the area is cleaned and dressed.

b. Equipment

Equipment used in this process except the pulverizers is of the

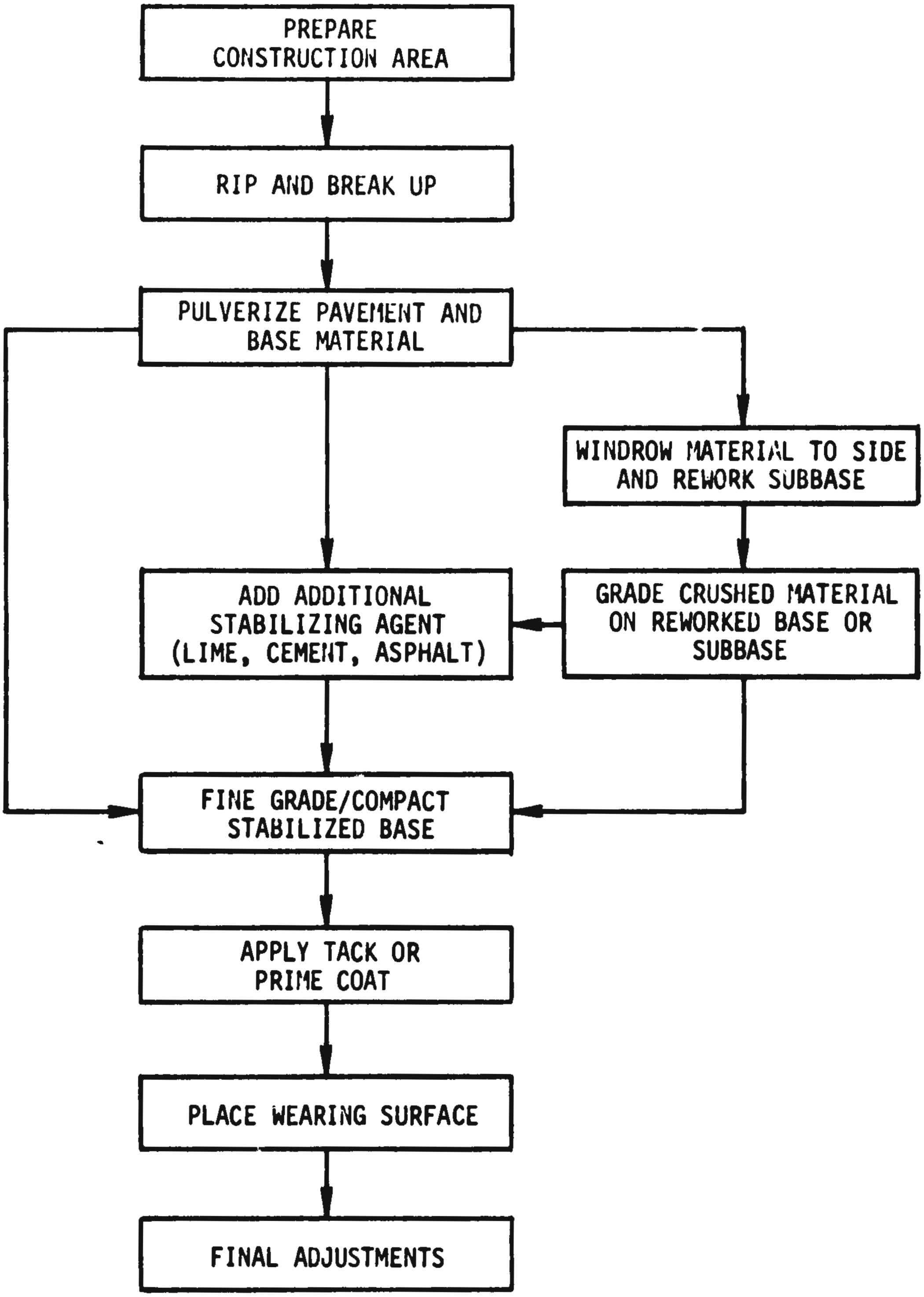

Figure 15. Process Flow Chart - Pulverize In-Place

standard road building type. Motorgraders with scarifiers or bulldozers with ripper teeth are used for the initial breakup. Heavy equipment, such as bulldozers, rollers and compactors, is used if further breakdown is required. Conventional distributors and mixers are used to spread and combine any additional stabilizing agent. Regrading of the subgrade or subbase and recycled base material is done by motorgrader, and compaction is accomplished with static steel-wheel, rubber-tired, or vibratory rollers. The new wearing surface is placed and compacted using conventional equipment and methods.

Two different pieces of equipment are currently being used for the actual pulverization of the old pavement. Independent Construction Company of Oakland, California, is using a Model 127 Metradon Pulverizer, and Bell and Flynn, Inc., of Stratham, New Hampshire, is using a Bros Preparator. Although these machines differ in design and operation, they produce very similar results.

The Metradon Pulverizer-Mixer is built using a scraper for the frame. The depth of the serrated cutting blade is controlled hydraulically. The Metradon is pulled by a bulldozer, and, as it moves forward, the material to be pulverized slides up into the scraper and is impacted by blades mounted on a high-speed shaft. There are 64 blades spaced on the shaft which rotates at 1250 rpm. The blades explode the asphalt concrete in midair. The pulverized material is laid back in a blanket ready for compaction or other treatment. The shanks of the pulverizing blades are 8 x 2 x 5/8 inches and are made of mild steel. Hardened steel pads, 2 x 2 x 1 inches, are welded to the leading edge of the shank. These pads are designed to last approximately 40,000 square feet or more, depending on the thickness and hardness of the asphaltic concrete. The Model 127 Metradon Pulverizer is capable of pulverizing asphaltic concrete to 90 percent, passing a 1- to 1-1/2-inch screen. Figures 16 and 17 show some general views of the Metradon Pulverizer-Mixer and its components.

The original pulverizer-mixer was designed for soil stabilization applications. By 1965 a technique was developed using the pulverizer-mixer to recycle old asphalt surfaces. The original patent and machines were under license to two successive contracting firms on an exclusive basis until January 1971. Since that time, Metradon International has redesigned and modernized the pulverizer-mixer. The current machine, Model PM-127 Series B, has the capability to work to a depth of 20 inches compared to 7 inches with the original model. No current cost for this equipment is available.

The Bros Preparator uses a different technique for pulverizing old asphalt pavements. The Preparator is a motorized traveling hammermill with a mixing chamber containing 22 hardened steel hammers. These hammers

Figure 16. Metradon Pulverizer-Mixer

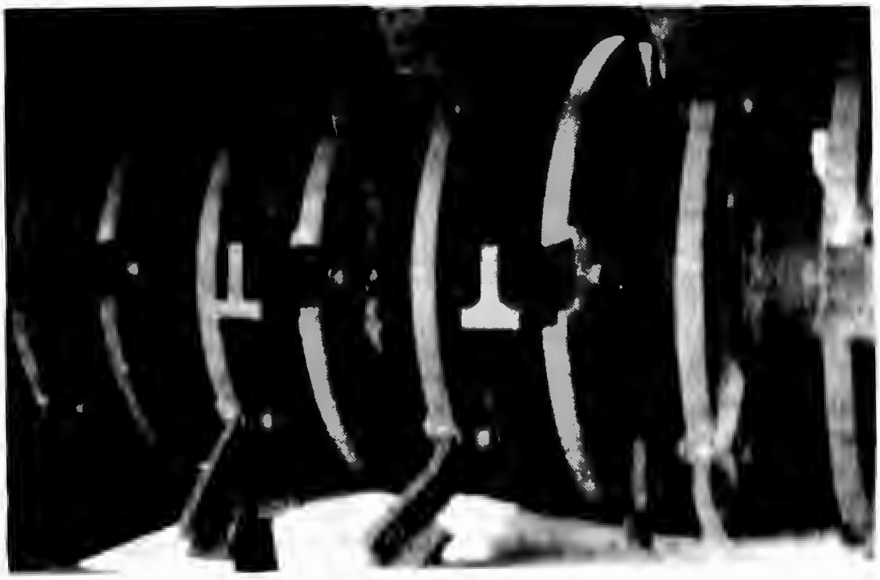

Figure 17. Close-Up of Shanks on High Speed Rotor of Metradon Pulverizer-Mixer

can break asphalt concrete and cobbles down to a maximum size of 2 inches. The length of the hammers wears down during a day's work from 18 inches to 6 inches. The Preparator can process 300 to 700 square yards of asphalt per hour. To work most efficiently, the material should be windrowed for processing through the Preparator. Figures 18 through 20 show some general views of the Preparator and its components.

Bell and Flynn, Inc., currently have four Preparators. Production of the machine by the Bros Division of American Hoist of St. Paul, Minnesota, was halted in 1967 due to lack of demand. At that time, a Preparator cost $25,000.

Maintenance is the biggest problem in the operation of both the Metradon Pulverizer-Mixer and the Bros Preparator. Pads in the Metradon and hammers in the Bros hammermill have a high wear rate. Changing the pads or hammers is an expensive and time-consuming operation. In 1973 the cost of changing hammers on the Bros Preparator was $300.

c. Technical Aspects

In situ reprocessing of asphaltic concrete pavements as untreated base material has been done for a number of years. Recent developments of in-place processing equipment and techniques have further emphasized the advantages of using recycled bases in lieu of conventional overlays or reconstruction with virgin-select materials. Additional cementing agents, such as lime, cement, and asphalt, can be incorporated into the pulverized mix to produce optimally stabilized bases.

There are several advantages of in-place processing. Equipment required for the process is minimal and processing in-place affords the opportunity to correct structural and material problems quickly and, therefore, without protracted disruption of traffic. The residual asphalt or cement in recycled untreated bases or in recycled treated bases, where stabilizing agents have been added, act as an excellent binder to help make the recycled base waterproof and less frost susceptible. Generally the load-bearing capacity of the pavement is also increased. With an increased load-bearing capacity in the base course, the pavement structure could be constructed thinner. A thinner pavement structure would mean less total materials required and, therefore, a savings of virgin-select materials. Another advantage is that any material generated as waste due to grade requirement of the new surface course will be good quality base material which can be sold or stockpiled for future use.

Using the Metradon Pulverizer-Mixer, Independent Construction Company has reconstituted old asphalt pavements into both untreated and treated base courses. Lime and cement, or a mixture of both, have been

Figure 18. Bros Travelling Hammermill

Figure 19. Bros Travelling Hammermill in Operation

Figure 20. New and Used Pulverizing Hammers

used as an additional stabilizing agent to construct the reconstituted base courses. Independent Construction Company has developed specifications for construction of these bases using pulverized asphalt concrete but recommends that a consulting engineer or materials testing laboratory familiar with job materials perform the actual design. The amount of lime or cement required in the treated bases is determined using basic soil-cement tests (freeze-thaw, plasticity, etc). Thickness of the new wearing surface is determined from the load-bearing capacity of the reconstituted base.

In 1973 Independent Construction Company used their Metradon Pulverizer-Mixer in the reconstruction of a runway and taxiway at Douglas County Airport, Minden, Nevada. The existing 3- to 3.5-inch asphalt concrete surface had received little or no maintenance since its construction by the Corps of Engineers in 1943. Although there was no apparent structural damage, the pavement had become very brittle and had a random crack pattern throughout with grass growing in the cracks. The airfield has been used mainly by small private aircraft. Redesign and field control were performed by Reinard W. Brandley, Consulting Civil Engineers, Sacramento, California.

The job consisted of pulverizing the old asphalt pavement to minus 2 inches and blending it with base material below to create a new untreated 6-inch aggregate base compacted to 100 percent relative compaction (modified proctor) and overlaying the base with a new asphalt concrete wearing surface. Tables 7 and 8 show summaries of field control tests for gradation and compaction.

In late summer of 1974, Independent Construction Company, acting as a subcontractor to Teichert Construction of Sacramento, California, completed a street reconstruction project at Incline Village, a subdivision at Lake Tahoe, Nevada. Severe deterioration of the pavement structure was occurring because of inadequate initial construction and excessive loading by heavy snow removal equipment. Environmental restrictions require all waste materials to be hauled out of the Tahoe Basin for disposal and all new construction material to be imported. Reconstruction using the in-place materials was considered the most feasible environmental and economic solution.

Using the Metradon Pulverizer-Mixer, the existing 1- to 6-inch asphalt concrete pavement was pulverized to 90 percent minus 1-1/2 inches. The pulverized pavement was mixed with the decomposed granite base material, and 4 percent by weight cement was added to create a 6-inch cement-treated base. An MC-250 was used for a prime coat. A 2-1/2-inch asphalt concrete wearing surface was constructed on the stabilized base. Performance over one winter season has been very good with no deterioration. Figure 21 is a photo showing the pavement after one winter season as well as the condition of an intersecting street that is typical of the pavement condition

TABLE 7. REUSED MATERIAL FIELD CONTROL TEST RESULTS: DOUGLAS COUNTY AIRPORT, MINDEN, NEVADA[a]

RECONSTRUCTION OF RUNWAY 16-34
RECONSTRUCTION OF TAXIWAY F

CONSTRUCTION OF GENERAL AVIATION AND ITINERANT APRON
LIGHTING OF RUNWAY 16-34 AND TAXIWAY F

SUMMARY OF FIELD CONTROL TESTS - REUSED A.C. MIXED WITH REUSED A.B. GRADING ANALYSIS - PERCENT PASSING

Sample No.	Location of Sample	Date of Test	3-Inch	2-Inch	1-1/2-Inch	No. 10	No. 40	Wash No. 200	Remarks
1	Runway Intersection	5/24/73	100	--	97	36	13	6.7	Pulverized A.C.
2	R/W 16-34 33+00 10'R	6/20/73		100	100				Pulverized A.C.
3	R/W 16-34 33+00 10'L	6/20/73	100	--	98	36	17	8.8	After Mixing
4	R/W 16-34 44+00 2.5'R	6/20/73		100	96				Pulverized A.C.
5	R/W 16-34 44+00 10'L	6/20/73	100	--	97	32	13	7.0	After Mixing
6	R/W 16-34 55+00 7.5'R	6/20/73		100	94				Pulverized A.C.
7	R/W 16-34 55+00 7.5'L	6/20/73	100	--	97	36	15	7.1	After Mixing
8	R/W 16-34 67+00 12.5'L	6/26/73	100	100	95				Pulverized A.C.
9	R/W 16-34 67+00 Centerline	6/26/73	100	100	99	35	15	7.0	After Mixing
10	R/W 16-34 77+00 12.5'L	6/26/73	100	100	96				Pulverized A.C.
11	R/W 16-34 77+00 10'R	6/26/73	100	100	98	35	14	7.2	After Mixing
12	R/W 16-34 88+00 15'L	6/26/73		100	95				Pulverized A.C.
13	R/W 16-34 88+00 7.5'R	6/26/73	100	--	96	35	14	6.1	After Mixing
14	R/W 16-34 99+00 12.5'L	6/26/73			100				Pulverized A.C.
15	R/W 16-34 99+00 10'R	6/26/73	100	--	100	31	13	7.3	After Mixing
	Specifications		--	100	90-100	--	--	--	Pulverized A.C.
			100	--	--	20-100	5-60	0-15	After Mixing

[a] This table of test results was obtained from Reinard W. Brandley, Consulting Civil Engineers, Sacramento, California.

TABLE 8. SUMMARY OF FIELD COMPACTION TEST RESULTS USING PULVERIZING-MIXING PROCESS: DOUGLAS COUNTY AIRPORT, MINDEN, NEVADA[a]

Test No.	Date	R/W or T/W Station	Offset From Centerline	Depth From Top of Sub-grade of Lift	Moisture Content Percent	Dry Density pcf	Maximum Dry Density pcf	Relative Compaction Percent	Remarks
1	6/14/73	T/W F 0+10	On Centerline	-0.0'	4.0	133.2	131.3	100+	
2	6/14/73	T/W F 2+60	T/W F, 5' R	-0.0'	6.5	127.9	131.1	97.6	
2A	6/15/73	T/W F 2+60	T/W F, 5' R	-0.0'	6.9	136.6	133.7	100+	Retest 2
3	6/14/73	R/W 16-34 62+35	10' R	-0.0'	7.2	132.3	131.9	100+	
4	6/14/73	R/W 16-34 65+25	25' R	-0.0'	6.9	133.6	128.7	100+	
5	6/14/73	R/W 3-21 58+00	35' R	-0.0'	4.5	134.0	129.1	100+	
6	6/14/73	R/W 12-30 58+50	20' R	-0.0'	4.8	126.5	132.1	95.8	
6A	6/15/73	R/W 12-30 58+50	20' R	-0.0'	7.3	132.4	132.1	100+	Retest 6
7	7/2/73	R/W 16-34 33+00	15' L	-0.0'	3.4	130.5	120.0	100+	
8	7/2/73	R/W 16-34 45+00	10' R	-0.0'	5.3	129.5	123.4	97.1	
8A	7/5/73	R/W 16-34 45+00	10' R	-0.0'	4.2	132.2	132.2	100	Retest 8
9	7/2/73	R/W 16-34 58+00	25' L	-0.0'	6.8	130.0	130.0	100	
10	7/3/73	R/W 16-34 40+50	20' R	-0.0'	6.2	128.4	131.1	97.9	
10A	7/5/73	R/W 16-34 40+50	20' R	-0.0'	4.6	134.4	132.5	100+	Retest 10

NOTE: Embankment measured from top of subgrade unless otherwise noted. Base and subbase measured from top of applicable section in lifts.

Specification Requirement: 100% Minimum Relative Compaction (Modified Proctor).

[a] This table of test results was obtained from Reinard W. Brandley, Consulting Engineers, Sacramento, California.

TABLE 8. SUMMARY OF FIELD COMPACTION TEST RESULTS USING PULVERIZING-MIXING PROCESS: DOUGLAS COUNTY AIRPORT, MINDEN, NEVADA[a] (CONCLUDED)

Test No.	Date	R/W or T/W Station	Offset From Centerline	Depth From Top of Sub-grade of Lift	Moisture Content Percent	Dry Density pcf	Maximum Dry Density pcf	Relative Compaction Percent	Remarks
11	7/3/73	R/W 16-34 50+50	15' L	-0.0'	8.2	145.3	136.0	100+	
12	7/6/73	R/W 16-34 70+50	20' R	-0.0'	5.6	133.6	133.7	100	
13	7/6/73	R/W 16-34 83+75	10' R	-0.0'	5.6	135.9	134.9	100+	
14	7/9/73	R/W 16-34 76+00	10' L	-0.0'	3.5	130.9	130.8	100+	
15	7/9/73	R/W 16-34 90+00	25' L	-0.0'	5.8	139.9	134.9	100+	
16	7/9/73	R/W 16-34 96+00	20' R	-0.0'	3.8	139.8	136.7	100+	
17	7/10/73	T/W B 49+75	T/W B, 5' R	-0.0'	5.2	139.6	135.0	100+	
18	7/10/73	T/W F, 6+00	T/W F, 5' R	-0.0'	7.0	132.2	130.8	100+	
19	7/10/73	T/W F 4+25	T/W F, 15' L	-0.0'	2.8	135.3	129.8	100+	

NOTE: Embankment measured from top of subgrade unless otherwise noted. Base and subbase measured from top of applicable section in lifts.

Specification Requirement: 100% Minimum Relative Compaction

[a] This table of test results was obtained from Reinard W. Brandley, Consulting Engineers, Sacramento, California.

Figure 21. Incline Village Project (Recycled Pavement in Foreground with a Typical Deteriorated Section in the Background)

before recycling.

After completion of the Incline Village reconstruction project, Independent Construction Company undertook a somewhat similar recycling project directly for the State of California, Department of Transportation, District 3, Marysville. The project took place on a 3-mile section of Yolo 45 located in the Sacramento Valley. Yolo 45 is a secondary State highway primarily carrying heavy trucks loaded with equipment and farm products. The road has been maintained by patching and sections of overlay. The pavement subgrade is clay with a high water table. The asphalt concrete surface varied in thickness from 3 to 9 inches and had deteriorated severely in some areas due to the heavy truck loads. Reconstruction by conventional means was not economically feasible or environmentally advantageous, so the California Department of Transportation chose to recycle the in-place materials with the addition of lime to form a stabilized waterproof base for a new wearing surface.

Using the Metradon Pulverizer-Mixer, the existing asphalt concrete pavement was pulverized to 90 percent minus 1-1/2 inches. The pulverized pavement was mixed with the clay subgrade material, and 4 percent by weight lime was added to create a 10-inch compacted lime-treated base. A prime coat was applied using 0.2 gallon per square yard of CRS-2 asphaltic emulsion followed by a light sand coating. Since the project was undertaken in the late fall of 1974, application of a 2.5-inch asphalt concrete wearing surface was delayed until the spring of 1975. The overall project produced a firm, stable base material and required repair of only a few potholes before application of the asphalt wearing surface.

The California Department of Transportation is currently finalizing a detailed report on the Yolo 45 project.

Bell and Flynn, Inc., has been recycling old asphalt pavements into untreated base courses since 1964. Using the Bros Traveling Hammermill, they have recycled highway and airfield pavements varying in thickness from 2 inches to greater than 10 inches.

As part of their recycling, Bell and Flynn, Inc., evaluate in situ material prior to doing a project. The evaluation involves determining the asphalt content and gradation of the asphalt concrete and gradation of the existing base material. From this information and experience with pulverizing effects of the hammermill, a final blend is proportioned with a residual asphalt content of approximately 3 percent which will give maximum density. The required thickness of the new wearing surface is then determined from the load-bearing capacity of the reconstituted base.

In 1972 Bell and Flynn, Inc., used their reconstitution process in the reconstruction of a runway at Orange Municipal Airport, Orange, Massachusetts. The existing 2-inch asphalt concrete surface was badly cracked and had received little maintenance since its construction during World War II as an Auxiliary Air Corps Airfield. Numerous cobbles (6- to 12-inch-diameter stones) had moved by frost migration from the subbase to the base and were causing surface irregularities. Rather than remove and waste the existing pavement, it was determined that it would be economically advantageous to reconstitute and reclaim it.

Field explorations were performed, and the average gradations of the existing pavement and base were as follows:

TABLE 9. FIELD GRADATION

Sieve Size	Percent Passing by Weight Base	Pavement
1 inch	100.0	100.0
3/4 inch	92.1	90.5
1/2 inch	84.8	75.3
3/8 inch	80.3	68.9
No. 4	71.4	53.0
No. 10	61.0	41.1
No. 20	46.4	29.0
No. 40	30.3	16.3
No. 80	14.1	6.9
No. 200	4.3	2.7

By analyses of the pulverizing effects of the hammermill and these gradations, it was determined that a blend consisting of the 2 inches of existing pavement and 4 inches of existing base would yield the calculated gradation shown below. The oversized cobbles in the existing base could not be pulverized to less than 2-inch maximum size; therefore, the gradation requirements in Federal Aviation Administration Item P-208 specifications for bituminous base course were waived, and the job gradation specification used as shown below. Oversized cobbles were removed by hand during the crushing operation.

TABLE 10. JOB SPECIFICATION GRADATION

Sieve Size	Calculated Blend	Percent Passing by Weight FAA Item P-208 Specification	Job Specification Used
2 inch	100	100	100
1 inch	88	100	80-100
3/4 inch	83	70-100	75-100
No. 4	54	35-65	47-70
No. 40	16	15-30	10-25
No. 200	1.2	5-15	1-8

The average gradation during the construction was as follows:

TABLE 11. AVERAGE AS-CONSTRUCTED GRADATION

Sieve Size	Percent Passing by Weight Results	Specification Range
2 inches	100.0	100
1 inch	89.9	80-100
3/4 inch	87.3	75-100
1/2 inch	77.3	--
3/8 inch	71.1	--
No. 4	57.6	45-70
No. 10	45.7	--
No. 20	33.7	--
No. 40	22.1	10-25
No. 80	11.4	--
No. 200	3.2	1-8

The original asphalt content of the pavement was 6.1 percent, and after blending with the base course, the composite asphalt content averaged 2 percent. Compaction was accomplished at ±1 percent of optimum moisture content, and the required compaction of 100 percent of proctor density was obtained. A light fog application of bituminous tack coat (0.05 gallon/square yard) was applied to the reconstituted base, and a new 2-inch asphalt concrete wearing surface was placed.

d. Economic Aspects

The in-place processing of old asphalt concrete pavements into untreated and treated bases offers some distinct economic advantages over conventional reconstruction. All of the costs associated with disposal of the old pavement and acquisition of new base material are eliminated. Elimination of hauling large amounts of demolition and construction materials also reduces maintenance requirements on access roads to reconstruction projects. Savings are also experienced in the amount of material required for new asphalt concrete wearing course. Due to the increased bearing capacity of the reconstituted base, a thinner asphalt wearing surface is required. Besides these and other purely economic advantages, in-place processing has proven to be more economical with respect to time than conventional reconstruction.

Prior to 1974, Independent Construction Company estimated a cost of $0.12 to $0.15 per square foot for recycling in-place material with 3 percent lime or cement to produce a stabilized base. The price for pulverizing the asphalt alone to 1-1/2 or 2-inch maximum particle size was estimated to be $0.03 to $0.06 per square foot, depending upon size of the job, thickness of the asphalt concrete, and other competitive factors.

In projecting these competitive factors to assumed project conditions, Independent Construction Company estimates the costs of recycling by pulverizing in-place can be as much as 50 percent of that of reconstruction by removing the old material and bringing in virgin-select materials. This projection is based on a nearby disposal area for waste material and a nearby source of quality base aggregate. The savings in time by using in-place processing can significantly contribute to reduction in project costs.

For the Incline Village reconstruction project where both disposal areas and new aggregate sources were not readily available, savings were estimated by the Washoe County officials to be approximately $50,000. Bid price for the project using in-place processing was approximately $156,000. Final project costs underran the bid by another $10,000. Part of the savings can be attributed to the fact that the project only required 27 of the original 45 scheduled calendar days for completion. This savings in time was crucial in an area such as Lake Tahoe where the construction season is relatively short.

The California Department of Transportation conducted a cost comparison study for the Yolo 45 project. Alternative 1 consisted of placing 1.5 feet of aggregate base over the existing section followed by 0.2 foot of a new bituminous concrete wearing surface, while alternative 2 consisted of in-place processing of the old asphalt surface with the addition of lime to create a stabilized base for the new wearing surface. The estimates for evaluating the two alternate reconstruction schemes, excluding the wearing surface which would have been the same, were as follows:

TABLE 12. COST COMPARISON - CALIFORNIA DEPARTMENT OF TRANSPORTATION YOLO 45

Alternate 1

Place and Compact New Aggregate Base

Item	Amount
Aggregate Base	$ 50,688
Hauling	95,040
Spreading and Compacting	44,592
TOTAL	$190,320

TABLE 12. COST COMPARISON - CALIFORNIA DEPARTMENT OF TRANSPORTATION YOLO 45 (CONCLUDED)

Alternate 2

Recycle In-Place Material

Item	Amount
Pulverize, Treat with Lime, and Compact	$153.960

This estimate shows the recycling process to be more economical. Actual cost of the recycling process was less than the estimate of $131,819 or, based on the aggregate base scheme, 30 percent less.

For the Orange Municipal Airport project constructed by Bell and Flynn, Inc., in 1972, contractors were permitted to bid on both the use of virgin materials and the use of recycled pavement processes. The successful bids of these alternatives were as follows:

TABLE 13. ORANGE MUNICIPAL AIRPORT CONSTRUCTION

Alternative A

Recycle Old Pavement, Mixing with Base

Item	Quantity	Amount
Unclassified excavation	50 cy	$ 250
Subbase (on site)	600 cy	6,600
Stabilized base course prep	32,500 cy	73,125
Bituminous tack coat	6,600 gal	7,260
Bituminous concrete	4,300 tons	58,050
Runway painting	1 s	3,000
TOTAL		$148,285

Alternative B

Discarding Old Pavement, Importing Virgin Material

Item	Quantity	Amount
Unclassified excavation	2,100 cy	$ 8,400
Offsite crushed aggregate	4,800 tons	50,400
Aggregate base course	32,500 sy	32,750
Bituminous prime coat	16,500 gal	8,250
Bituminous concrete	4,300 tons	58,050
Runway painting	1 s	3,000
TOTAL		$160,850

The contract was awarded to Bell and Flynn, Inc., on the basis of the alternative A low bid. Actual construction cost was $140,368, resulting in a 15 percent savings over the bid for conventional reconstruction.

Also in 1972, Bell and Flynn, Inc., reconstructed Wyman Street in Lynn, Massachusetts. The project consisted of pulverizing the existing asphalt concrete pavement, mixing it with underlying base material to form a stabilized base, and constructing a 2-inch asphalt concrete wearing surface over the reclaimed base. A cost comparison of this reconstruction process versus conventional reconstruction is as follows:

TABLE 14. COST COMPARISON RECONSTRUCTION OF WYMAN STREET, LYNN, MASSACHUSETTS

Reclamation (12-inch depth total)

Item		Cost
Base preparation (7,398 square yards)	BID	$15,000
	LABOR	--
Casting adjustments (manholes, catch basins)		1,200
Bituminous wearing surface (2 inch)		8,220
TOTAL		$24,420

Conventional Reconstruction (EST)

Item		Cost
Base preparation (7,398 square yards)	BID	$ --
	LABOR	9,700
Gravel replacement		4,200
Equipment costs, depreciation, full		9,100
Casting adjustments		1,200
Bituminous wearing surface		12,330
TOTAL		$36,530

e. Environmental Aspects

The environmental advantages of in-place processing of old asphalt pavements to produce recycled bases are essentially the same as those presented for the remove and crush procedure. Additionally, fuel usage is reduced by not having to haul the old pavement away and haul new pavement material to the project. Less fuel usage translates into less air pollution.

SECTION V

HEATER-PLANER SCARIFIER RECYCLING PROCEDURE

Total reconstruction of old asphalt pavements as described in the previous sections is necessary only when pavement distress is caused by structural defects or when reprocessing could effect an immediate or ultimate cost savings. Certain surface pavement defects, such as surface distortions, surface cracking, or low skid resistance, can be corrected by surface reprocessing. Processes such as heater planning or scarifying permit recycling or reusing at least a portion of the old asphalt pavement. Developments in heating techniques and improvements in equipment have minimized some of the problems previously encountered in attempting to heat and soften old asphalt pavements in-place. As an example of existing new equipment, Cutler Repaving, Inc., Lawrence, Kansas, has developed a machine called the Repaver which heats, scarifies, levels, and lays a new thin overlay in the same operation. Continued improvement in equipment and techniques will enhance the use of heater planers as a recycling alternative in repair and maintenance of asphalt pavements.

a. Process

The general process for rehabilitating old cracked asphalt pavements using heater planers is shown by the flow chart in Figure 22. This process is accomplished by a train of equipment usually consisting of two heater-planer scarifiers in tandem, a distributor, compaction equipment, and an asphalt paver followed by additional compaction equipment. First, in the process, proper drainage is restored where necessary, defective areas patched, and any large cracks cleaned and filled. The project area is then cleaned up. Tandem heater-planer or multiple passes of one machine processes the pavement to the desired depth, and a rejuvenating agent or emulsion is applied to the pavement. The treated pavement is rolled to press down large aggregate particles loosened by the scarifier, and then a thin overlay of new hot mix is applied. Finally, any adjustments to manholes or other structures are made and the area is cleaned up.

The proposed process for the new Cutler Repaver is shown by the flow chart in Figure 23 and is essentially the same as for other heater-planer scarifiers. However, the Repaver was designed to heat and plane-scarify to a depth of approximately 3/4 inch in one pass while operating at relatively high forward speeds. The rejuvenating agent or emulsion can also be applied by the Repaver. The treated scarifier material can be used as a leveling course over which an overlay of new hot-mix is applied. The new overlay is then rolled to the specified density, adjustments to structures such as manholes made, and the area cleaned up.

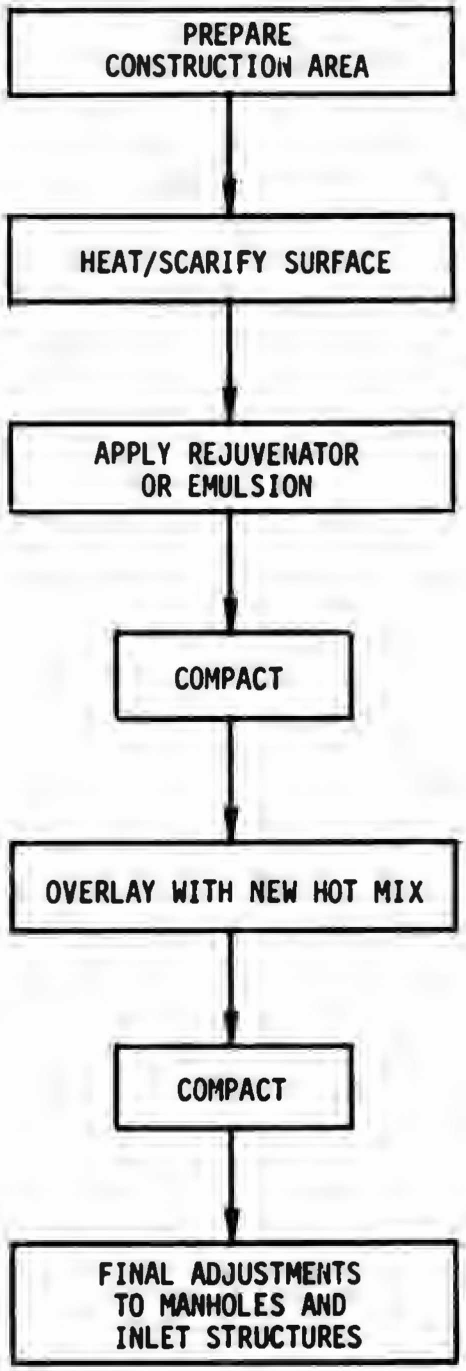

Figure 22. Process Flow Chart - Heater-Planer-Scarifier

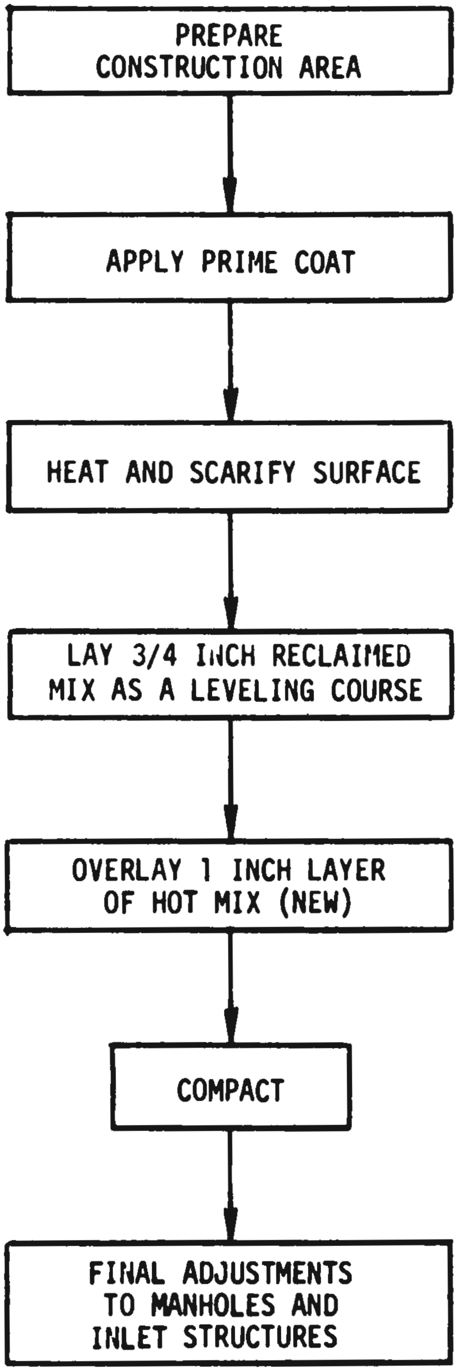

Figure 23. Process Flow Chart - Repaver

Cutler Repaving, Inc., also has recently completed development of a larger version of their Helio Planer called the Jumbo Helio Planer. The Jumbo was designed for use with the Repaver to provide the capability to rework a greater depth of pavement or to work in a train of equipment similar to the operation shown by the flow chart in Figure 22. For some deformed and slippery pavements that are rich in asphalt cement and require surface repairs, modifications of this basic process are also being considered. For instance, a conventional chip seal or a precoated chip seal can be used behind the Jumbo in lieu of an overlay.

b. Equipment

Existing heater-planer scarifiers generally operate on the same principle but they vary considerably in design and appearance. The basic components of a heater-planer are a heating system, scarifiers, leveling blades, and, in some cases, material-loading mechanism. Heating systems consist of either radiant heat emitters or open-flame burners. These emitters or burners are enclosed by a hood which directs the heat onto the pavement surface. Carbide tip steel blades or spring-mounted scarifiers loosen and process the heated pavement. Steel scraper blades may be available for leveling and also for gathering the excess material into a windrow to facilitate loading. Other options include automatic controls and spray bars for applying emulsions or rejuvenators.

The Cutler Repaver has the additional capability of placing a hot-mix overlay in the operation. It has a receiving hopper, conveyor system, and heavy-duty vibratory screed similar to those components on a conventional asphalt paver. It also has a set of leveling screws to assist in the leveling of the heated pavement before the overlay is applied. Figures 24 through 26 show some typical heater-planer units.

c. Technical Aspect

Heater-planers have been used for removing dead weight from bridges, maintaining proper clearance in tunnels and underpasses, removing surface irregularities from rough asphalt pavements, and processing to eliminate surface deterioration and improve skid resistance. Expanded experience and recent developments in heater-planer equipment and techniques have made the use of heater-planers potentially more advantageous for repair and maintenance of old asphalt pavements.

Until 1973 all heater-planers used open-flame burners to heat and soften the pavement. Direct flame contact with the pavement often produced a charred and burned surface as well as a dense cloud of black smoke (air pollution). In 1973, Cutler Repaving, Inc., developed equipment using ceramic cup radiant emitters. These emitters produce heat in the infrared range allowing more efficient heating. Radiant heat does

Figure 24. Cutler Repaver

Figure 25. Cutler Jumbo Helio Planer

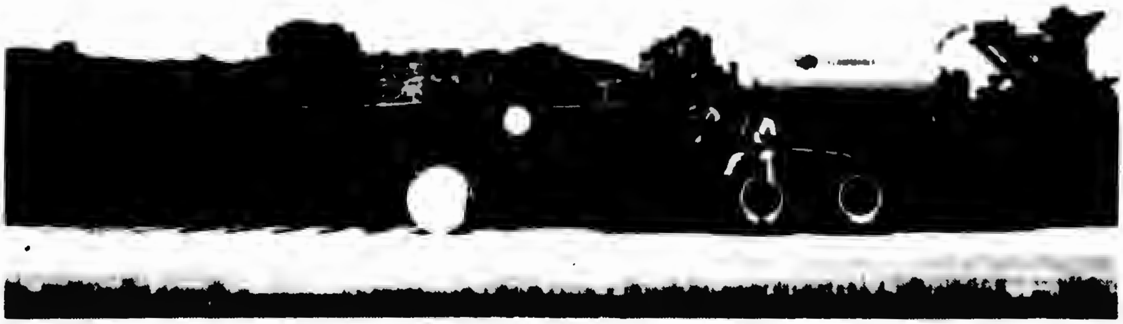

Figure 26. Jim Jackson Heater Planer

not burn or char the pavement surface and is smokeless.

The heater planing or scarification of an asphalt surface before application of an overlay or other type surface treatment does offer some advantages. Pavement surface distortions can be removed to provide a smooth surface for a new wearing course and therefore eliminate or reduce leveling course thickness. Curb lines and drainage can be maintained by planing off a portion of the existing surface before application of a new wearing surface. It is claimed that reflective cracking, which is a major problem with thin overlays, is somewhat retarded when the existing surface is heater-scarified before a thin overlay is applied. Actual experience indicates that reflective cracking may be retarded and may be less severe than a conventional thin overlay by itself. Skid resistance can sometimes be improved by heater-scarification. One process for improving skid resistance is to apply abrasive chips to a heater-scarified surface followed by rolling. Improved bonding between the overlay and the existing surface has also been experienced on some projects. Poor bond occurs where too much or the wrong kind of additive or emulsion is applied.

Past performance of projects using heater-planers and scarifiers has varied from good to bad. Some of the more obvious problems that have occurred from heater-scarifying are poor and sometimes complete lack of bond between the overlay and heater-scarified surface, poor penetration of the scarifier teeth or blades, poor grade control on scarifying-planer operations, large aggregate from the scarified pavement being dragged by screed on laydown machine, and most important, poor workmanship. Some of these problems are technical which could be solved by study; others are problems that could be solved by attention to detail.

d. Economic Aspects

If application of heater-planer scarifiers is done for the right reasons to the right project, repair and maintenance of asphalt pavement using heater-planers and scarifiers offers some economic advantages over conventional overlay methods. As mentioned above, heater-planing scarifying may eliminate or at least reduce the thickness of a leveling course and also reduce the thickness of new wearing course for a structurally sound pavement. By retarding reflective cracking, heater-planers could also extend the life of existing pavements and reduce their annual maintenance costs. Cutler Repaving, Inc., claims that 1-inch (100 pounds per square yard) new hot-mix on a heater-scarifier-planer surface is superior to 2-inches (200 pounds/square yard) applied by conventional methods. If this claim is valid, a savings of 704 tons of new hot-mix for every mile of 24-foot-wide pavement could be realized. This type of process would also result in a savings in fuel realized from decreased usage in production and transportation.

In 1974, the City of Topeka, Kansas, did a cursory cost study of street maintenance projects done using the Cutler Repaver and those done by conventional overlay. A summary is given in Table 15.

TABLE 15. CUTLER REPAVING 1974

	Cost	Cost/Sq Yd
Cutler repaving (198,862 sq yd-1 in.)	$100,011.72	$0.503
Emulsion	95,124.60	0.478
Apparent total cost per square yard		$0.981

Asphalt Overlay 1974

	Cost	Cost/Sq Yd
Asphalt concrete (91,323 yd-2 in.)	$138,212.67	$1.513

This summary does not include costs of men and equipment the city used to supply and spray the emulsion and provide traffic control. If the cost of the city's effort were included, the costs per square yard for Cutler Repaving would be slightly higher.

The City of Tampa, Florida, used the Cutler Repaver in its street maintenance program in 1971, 1973, and 1974. They estimate cost savings of approximately 30 percent over conventional overlay. This savings resulted mainly from less material. The City of Albuquerque, New Mexico, evaluated the cost for total replacement of a pavement and the use of a Cutler heater-scarifier-planer followed by a thin overlay. The cost for total replacement was $7.50 per square yard compared to $1.20 per square yard using the Cutler process. The costs for a given job will vary considerably, depending on such factors as the size of the project and the availability and costs of materials.

e. Environmental Aspects

The use of the heater-scarifier-planer and similar units in repair and maintenance of asphalt pavements does offer environmental advantages. Overall, significantly less material is required. This would reduce the demand for virgin-select aggregates and asphalt. Also noted was the reduced usage of fuel in production and transportation. There may be material generated as waste in the planing and leveling operation that could be used as base material on another project resulting in further savings of material. Reuse of this material would reduce the volume of waste pavement disposal.

The advent of radiant heat and better controls on open-flame burners can minimize the air pollution problem prevalent when asphalt pavements are heated and particles of asphalt are burned.

SECTION VI

OTHER RECYCLING METHODS

Under the general heading of other methods, there are at least two methods that should be mentioned with a brief discussion of each so that they might be placed in the proper context with the subject of recycling pavements. These two methods are pavement grinding and pavement rejuvenation.

a. Grinding

Recent developments in grinding equipment and techniques have increased efficiency and productivity considerably. One commercially available grinder called the Galion RP30 Road Planer has the capability of removing 4 inches of asphalt overlay at rates up to 19 fpm and 4 inches of concrete (nonreinforced) at rates of 8 to 10 fpm. Each pass cuts a 30-inch-wide section. Figure 27 shows the Galion RP30 Road Planer. Grinders provide a fast, economical solution to many of the problems caused by overlays, such as raising manholes and other structures and maintaining curb lines and drainage patterns. An added benefit of some grinders is that the material removed makes an excellent base material for roads, parking lots, etc. Reuse of the planned materials eliminates the need for disposal areas, while also making the process more economically advantageous.

b. Pavement Rejuvenation

Pavement rejuvenators are liquid materials, cutback or emulsion sprayed on a pavement surface. The claim is made that the pavement asphalt properties are improved and pavement cracks healed by these materials. Actual performance data of rejuvenators are reported in Air Force Weapons Laboratory report entitled "Evaluation of Rejuvenators for Bituminous Pavement." The philosophical application of rejuvenators should properly be considered for preventative maintenance rather than for pavement rejuvenation. Systematic, light applications of certain types of rejuvenators will (a) minimally reduce a pavement's skid resistance, (b) provide benefit to the pavement by holding surface fines in-place, (c) reduce raveling at cracks, and (d) possibly retard the rate of development of existing crack patterns. The pavement fines are retained by the coating action of rejuvenators. In addition, these rejuvenator materials affect the consistency of the pavement asphalt, improving its cohesion properties. This also helps to hold fines in-place as well as retard raveling and crack growth.

Figure 27. Galion RP30 Road Planer

SECTION VII

CONCLUSIONS

Based on a review of available literature and information, it is technically feasible and economically and environmentally advantageous to recycle pavements and paving materials for use in pavement construction and maintenance. Reuse of both the aggregate and binder components of old pavements is beneficial in a number of ways. The most significant are:

(1) Recycling helps conserve our rapidly dwindling supply of virgin-select materials.

(2) Recycling helps preserve our environment by decreasing the need for development of new material sources while also decreasing the need for waste disposal areas.

(3) Recycling helps conserve energy by decreasing the need for processing, hauling new materials to the job site, and hauling waste materials to disposal areas.

Continued improvement of recycling equipment and techniques will further enhance these benefits while also producing high quality pavements at a cost savings.

Table 16 provides a summary of methods and uses of recycled pavements.

TABLE 16. SUMMARY OF METHODS AND USES OF RECYCLED PAVEMENTS

Method	Recycled Pavement	Use and Potential Use
	MAJOR PROCEDURES	
Remove and crush	Asphalt, concrete, portland-cement concrete	Production of base course materials
Remove and reprocess	Asphalt concrete	Production of hot-mix asphalt concrete
	Portland-cement concrete	Production of new portland-cement concrete; use as aggregate in hot-mix asphalt concrete
Pulverize-in-place	Asphalt concrete	Production of stabilized and unstabilized base courses
Heater-planer	Asphalt concrete	Repair and maintenance of surface problems
	OTHER METHODS	
Grinders	Asphalt concrete, portland-cement concrete	Repair and maintenance of surface problems
Pavement rejuvenators	Asphalt concrete	Preventative maintenance

SECTION VIII

RECOMMENDATIONS

It is recommended that this program be continued to establish criteria for use of recycled paving materials in airfield pavements. The following outline presents a plan of study that will develop the necessary technical data to accomplish this purpose for the various processing methods, resulting material types, and application of these material types in the pavement structure.

a. A comprehensive laboratory study should be undertaken to:

(1) Determine what tests and limits should be used to measure the quality of paving materials being considered for recycling.

(2) Determine what tests and limits should be used to measure the quality of mixes produced from recycled paving materials.

(3) Determine the effect of additives on recycled paving materials.

b. A comprehensive field study including construction and observation of prototype test sections should be undertaken to:

(1) Develop construction specifications and procedures for each of the recycling processes.

(2) Define equipment requirements for each of the recycling processes.

(3) Establish performance characteristics for each of the different applications of recycled paving materials.

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BIBLIOGRAPHY

1. "Asphalt Recycled In-Place Forms Base for New Pavement," *Roads and Streets*, Vol. 117, No. 11, November 1974, p. 122.

2. "Basic Engineering Principles of Chemical Stabilization," Paper produced by Brewer Cote Asphalt Products, Inc., Miami, Florida.

3. Briggs, Robert C., "Pavement Crushed, Reused to Strength Runway Base," *Civil Engineering-ASCE*, Vol 43, No. 6, April 1973, pp. 82-83.

4. Coster, M., "The Yolo-45 Reconstruction," District 3, California Department of Transportation, Unpublished report, Marysville, California, March 1975.

5. "Crushing Converts Rubble Into Subbase Aggregate," *Roads and Streets*, Vol. 113, No. 10, October 1970, p. 74.

   "Crushing Converts Rubble into Subbase Aggregate," *Roads and Streets*, Vol. 114, No. 5, May 1971, pp. 44-45.

6. Dallaire, Gene, "Like to Cut Cost of Repaving Roads 25%," *Civil Engineering-ASCE*, Vol. 43, No. 6, April 1973, p. 84.

7. Dunning, R.L., Mendenhall, R.L., and Tischer, K.K., "Recycling of Asphalt Concrete, Description of Process and Test Sections," Presentation at annual meeting of AAPT, Phoenix, Arizona, February 1975.

8. Etheridge, David C., "Re-Cycling Process Turns Rubble to Aggregate, Curbs Unsightly Dumps," *Construction Methods and Equipment*, Vol. 53, No. 6, June 1971, pp. 90-93.

9. Fondriest, F.F. and Snyder, M.J., "Synthetic Aggregates for Highway Construction," NCHRP Report No. 8, Highway Research Board, 1964.

10. Gallaway, Bob M., et. al., "Feasibility of Using Highway Litter in Highway Construction and Maintenance," Texas Transportation Institute for U.S. Department of Transportation, December 1971.

11. Gallaway, Bob M., Ledbetter, W.B., and Epps, J.A., "Summary Report-Feasibility of Using Solid Waste in Highway Construction and Maintenance," Texas Transportation Institute, December 1971.

12. Marek, Charles R., Gallaway, Bob M., and Ling, Robert E., "Look at Processed Rubble-It's a Valuable Source of Aggregates," *Roads and Streets*, Vol. 114, No. 9, September 1971, pp. 82-85.

13. Marek, C.R., Herrin, M., Kesler, C.E., and Barenberg, E.J., "Promising Replacements for Conventional Aggregates for Highway Use," NCHRP Report No. 135, Highway Research Board, 1972.

14. "Mobile Crusher Turns Waste Rock into Profits," Roads and Streets, Vol. 113, No. 12, pp. 44-45, December 1970.

15. "Old Asphalt can be Valuable Raw Material," Roads and Streets, Vol. 117, No. 6, June 1974, pp. 105-106.

16. "Old Asphalt for New Roads Offers Shortcut to Savings," Construction Methods and Equipment, Vol. 57, No. 5, May 1975, pp. 78-80.

17. "On-Site Material, Low-Cost Runways," Better Roads, Vol. 40, No. 12, December 1970, pp. 12-13.

18. "Planer-Key to Street Recycling," Roads and Streets, Vol. 118, No. 1, January 1975, pp. 60-61.

19. "Reclamation Process Cuts Street Construction Costs by 35%," The American City, Vol. 88, No. 3, March 1973, pp. 67-68.

20. Recycled Asphalt Concrete by RMI Systems, State of Nevada, Department of Highways, 1975.

21. "Recycled Roads and Buildings with Portable Plants," Pit and Quarry, Vol. 65, No. 8, February 1973, pp. 91-93.

22. "Recycled Rubble Saves Contractors Money," Roads and Streets, Vol. 116, No. 4, April 1973, pp. 80 and 83.

23. "Recycling Rubble for Highway Purposes," Public Works, Vol. 103 No. 10, October 1972, pp. 87-88.

24. "Reprocessed Asphalt Gets First Highway Test," Roads and Streets, Vol. 117, No. 12, December 1974, pp. 28-30.

25. "Road Planer Ends Problems of Overlay Build-Up," Construction Methods and Equipment, Vol. 57, No. 4, April 1975, pp. 40-41.

26. Sadler, Thomas B., "A Crushing Success: Aggregate from Concrete," Public Works, Vol. 104, No. 4, April 1973, pp. 72-73.

27. "Streets Stabilized with Chemical Plus Cutback," Rural and Urban Roads, Vol. 12, No. 1, January 1974, pp. 20-21.

28. "Toronto Saves Asphalt and $$$," Better Roads, Vol. 40, No. 12, December 1970, pp. 14-15.

29. "Use of Waste as Material for Highways," U.S. Department of Transportation, Federal Highway Administration, Project No. 4-C, September 1, 1971.

30. "Recycled Concrete," Miscellaneous Paper No. C-72-14, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi, May 1972.

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