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1 highway transportation
4 air transportation

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24 pavement design and performance
31 bituminous materials and mixes
33 construction
40 maintenance
41 construction and maintenance equipment

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Contents

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INTRODUCTION

The National Seminar on Asphalt Pavement Recycling was conducted by the Transportation Research Board (TRB) under the sponsorship of the Federal Highway Administration (FHWA), U.S. Department of Transportation. The seminar covered all aspects of asphalt pavement recycling, including surface, hot and cold recycling in both rural and urban situations. It was designed to help the beginner or novice to understand what is involved in the selection of a project for recycling and what are the advantages and disadvantages of the various types of recycling. Cost and energy considerations, specifications, quality control, and environmental considerations were addressed. Examples of both rural and urban projects were reviewed for each type of recycling. Equipment of all types was discussed, and research currently under way was reviewed. Adequate discussion time was allotted for all topics.

Attendance at the seminar was open to all interested parties. The seminar was designed to be of particular interest to state, city, and county engineers and to those responsible for formulating programs of construction or rehabilitation as well as contractors involved in or planning to bid on recycling projects.

The seminar was attended by 419 persons from the following types of organizations.

States and Canadian Province	75
Commercial (Contractors, Consultants, Materials Suppliers, etc.)	240
Academic	17
Cities and Counties	34
Federal Government	44
Other	9

The following geographical areas were represented.

United States	373
North America	18
South America	3
Europe	20
Africa	2
Asia	3

ECONOMICS OF RECYCLING

Sanford P. LaHue, Federal Highway Administration

As a result of spiraling highway construction costs, the highway community is deeply concerned with identifying cost saving measures in planning, designing, constructing, and maintaining streets and highways. One cost saving measure that has been identified, researched, and demonstrated is asphalt pavement recycling. Labor, materials, and energy savings have resulted on many projects. Continued development of recycling equipment, identification of new, innovative processes and widespread use of available information are among the elements needed to refine the state-of-the-art practices. As petroleum products and quality aggregates become more scarce, recycling of pavements will emerge as a standard highway and street construction item.

The desirability of conserving resources and the increasing cost of construction materials have recently led many road building agencies to consider a pavement rehabilitation alternative called recycling. Among the specific factors that have caused the highway community to take a serious look at pavement recycling is inflation, the decreasing availability of good quality aggregates, reduced gasoline tax revenues, rising petroleum prices and the ever present threat of another oil embargo by OPEC countries.

Along with the entire highway community, the Federal Highway Administration (FHWA) has been deeply concerned about items just mentioned and their pronounced effect on the cost of highway construction. As we are aware, the FHWA construction cost index has increased more rapidly than the consumer price index since 1967. The FHWA is both disturbed and concerned about this rapid rise when we keep in mind that highway program managers are now stretching every dollar almost to the breaking point to meet their needs. In many cases there aren't enough dollars to go around.

Highway obligations have more than doubled since 1967, but as a result of inflation we have fewer real dollars to work with now, as compared to then, when our needs seem greater than ever.

Paving has also contributed to this significant rise in costs. Asphalt and portland cement concrete paving have almost kept abreast of the construction cost index.

The highway community has responded to these increased costs. To survive, industry has identified new equipment and new methods. Local, State, and Federal governments have taken close scrutiny of their operations to identify cost saving strategies. Research has been identified and undertaken.

The FHWA has been fighting the rise in costs or inflation for several years now. The biggest mandate we have had was President Carter's Wage Price Guidelines and resulting order by former Secretary Adams to develop an anti-inflation program. From that order, the FHWA developed and issued FHWA Notice N 5080.83 in March 1979. This Notice contained several anti-inflation measures. One of these measures is recycling of pavements.

This was not a new-found program area. As a result of great cost saving potential, the FHWA, nearly 3 years earlier in June 1976, formally initiated Demonstration Project 39, "Recycling Asphalt Pavements."(1) This project was developed and administered from our Region 15 Office in Arlington, Virginia.

The project was developed to promot various techniques of asphaltic pavement recycling. Since June 1976, FHWA has given over one hundred presentations on this subject in this country and Canada to over 14,000 individuals. The "Demo 39" project has provided partical funding for the construction and evaluation of approximately 50 demonstration installations concerning hot, cold, and surface recycling.

Through this project and many State projects, recycling has been determined to be a cost-effective method when used on a project-by-project basis. As new equipment is developed and further experience is gained, we must include this pavement rehabilitation method as a worthy alternative.

Recycling offers many potential benefits. Three of the major ones are cost reductions or savings, energy savings, and the conservation of natural resources.

On many projects, total cost is the primary consideration in determining the type of rehabilitation procedure to use. For recycling to be selected, it must usually be the least expensive of the alternative methods. Several highway agencies have conducted cost analyses on completed recycling projects. These analyses have compared the actual cost of the recycling projects (using bid prices) to the estimated cost of the same projects using the rehabilitation procedure that would have been selected had recycling not been available. Most of the agencies have reported cost savings as a result of recycling.

Examples of reported savings include:

1. $146,000 saved on a 47,896 ton project. $3.05 per ton savings (Wyoming)

2. $59,385 saved on a 60,700 ton project. $0.98 per ton savings (Oregon)

3. $138,418.33 saved on a 42,129 ton project. $3.29 per ton savings (Iowa)

It is important to point out that recycling is still a relatively new technique to some contractors; therefore, bid prices on several projects have probably been somewhat higher than they would have been if recycling was a standard rehabilitation procedure. Bid prices have been slightly inflated by the fact that contractors must recover the cost of the necessary plant modification for, say, hot recycling. Because of the experimental nature of recycling, most contractors have seemingly tried to recover this additional cost immediately. Once recycling becomes a standard procedure, contractors will be more willing to write off the initial capital expenditure for plant modifications over several projects. As a result, it will probably be several years before the true cost of recycling is realized and the actual cost savings can be accurately determined. Based on figures from past projects, it is reasonable to assume that recycling offers potential cost savings in the neighborhood of 30 percent over conventional rehabilitation methods, when lide amounts of asphalt mix tonnage or pavement thicknesses are compared.

For many years, energy consumption on highway construction and maintenance projects was not a very important consideration. With the uncertain status of petroleum supplies during recent years, the former situation is changing. Energy consumption may become a primary factor in determining which rehabilitation methods are used on our existing highways.

Recycling can conserve substantial amounts of energy on many projects when compared to conventional rehabilitation methods. In determining energy savings, many factors must be considered for each project, including such factors as:

1. Amount of virgin aggregate required

2. Virgin aggregate haul distance

3. Amount of new asphalt cement required

4. Asphalt cement haul distance

5. Pavement removal method

6. Pavement crushing method

7. Haul distance from the project to the nearest pavement disposal site

8. Haul distance from the project to the crushing/mixing plant

9. Type of mixing plant

10. Moisture content of the salvaged asphaltic concrete and virgin aggregate

Three of the above items--virgin aggregate haul distance, amount of new asphalt cement required, and asphalt cement haul distance--will usually be the major factors in determining the potential energy savings of a recycling project compared to a conventional rehabilitation project.

Some recent typical projects have shown energy savings as much as:

1. 1.9 billion BTU's saved on a 53,000 ton project. Energy savings equivalent to 15,180 gallons of gasoline.

2. 3.8 billion BTU's saved on a 47,900 ton project. Energy savings equivalent to 30,220 gallons of gasoline.

3. 151 million BTU's saved on a 60,700 ton project. Energy savings equivalent to 1,210 gallons of gasoline.

The third major benefit of recycling is the conservation of natural resources. Both asphalt cement and virgin aggregates have the potential to be saved on every recycling project. To give an indication of the magnitude of these savings, the following figures have been accumulated from 27 major hot-recycling projects:

Recycle Mix (Total)	1,182,000 tons
Virgin Aggregates Conserved	771,000 tons
Asphalt cement conserved	42,800 tons

Cost savings, energy savings, and the conservation of natural resources are not the only potential benefits from recycling. Others may include:

1. Increasing the structural strength of the pavement without increasing its thickness

2. Correcting existing mix deficiencies

3. Correcting base problems

4. Eliminating reflective cracking problems

5. Maintaining curb, inlet, and manhole elevations along with existing drainage patterns

6. Maintaining overhead structure clearances

To take a more detailed look at the economics of recycling, I'd like to go through a series of slides showing several recycling projects which documented cost comparisons. Complete, bound reports are available for each of these projects should anyone want the complete story behind these project. I will only cover the project background and cost data.

The first project is in Millard County, Utah, (2) on Route U.S. 50. The pavement was recycled in September of 1977 and the project was 9.1 miles in length. The contract consisted of removing, crushing and stockpiling the old pavement; raising and widening the grade; recycling the reclaimed pavement; and relaying the recycled material on the finished subgrade. The contract was bid April 19, 1977.

The hot mix recycling method was used in a dryer drum plant.

The original roadway was constructed in the 1940's and widened to 21 feet in the 1950's. The average pavement depth was 3.3 inches. The pavement was constructed of roadmixed bituminous surfacing and had been repaired many times. Several type "A" cover aggregate courses had been applied to the surface.

The new recycled pavement was placed three inches thick at a finished width of 28 feet. There was approximately 21,800 tons of recycled material and 7,100 tons of conventional mix produced and laid.

There was a savings of $2.36 per ton when a comparison was made between the actual bid cost of the recycled asphaltic concrete and the actual bid cost of virgin asphaltic concrete on this project.

The second project is in Hidalgo County, Texas, (3) on Loop 374 between State Route FM 2062 and U.S. 83. The project was completed in May 1976 and was 1.5 miles in length. The project consisted of salvaging asphaltic material from State Highway 336 in Hidalgo County during construction on an active project. The pavement section of SH 336 consisted of a two course surface treatment applied in 1955, a 1¼ inch hot mix asphalt concrete overlay in 1959, and another surface treatment in 1964 for a total of approximately 2.5 inches. The recycled material was then to be laid as an overlay on Loop 374.

The type of pavement relaid, by hot recycling, consisted of three different mixes in three sections. These included 1) a mix using AC-3 asphalt adding up to 2.5 percent by weight, 2) a mix using flux oil added up to 1.6 percent by weight, and 3) a mix using Reclamite added at 1.6 percent by weight.

The cost analysis for this project showed that the recycled material was nearly the same as a new hot mix asphalt concrete mixture in place. However, project personnel conclude that had it not been for construction inefficiencies, i.e., equipment problems, incorrect estimating of haul distances, and equipment and labor costs, the potential savings could have been $4.80/ton. I must also add that this was one of the first recycling projects attempted. A lot was learned by the Texas Highway Department and FHWA on this project.

The third project is located in Republic County, Kansas (4). It is a cold recycling project. The project was located on a county road and was two miles in length. Construction took place in July 1977. The project consisted of tearing up and pulverizing the existing surface, adding a predetermined amount of asphalt, then relaying the mix. The first mile was to be constructed with emulsified asphalt (mix and seal) and the second with cutback asphalt, also for the mix and seal.

The original surface was constrcuted in 1963 as a 5 inch sand-gravel subgrade modification project. The subgrade modification was surfaced in 1964 with an asphalt prime and dougle seal. In 1972, a 2 inch road mix asphalt overly with a swal coat was applied. During the period from 1964 to 1974 there have been two reseal applications with periodic asphalt patching.

The cost analyses for this project reveals that there was a savings of $26,644.56. The labor and equipment costs for recycling cost more but the significant savings resulted in the material costs.

The fourth project I want to cover is a hot-recycling project in the State of Virginia (5). I talk about this project to give a realistic view about recycling and some of the growing pains of new technology. This project was nearly 1 mile in length and located on U.S. Route 1 in Chesterfield County near Richmond. The project took place in 1976 and 1977.

A conventional asphalt batch plant was used. Two evaluations were to be made. The first considered the process in which the recycle mix is introduced into the cold feed and proceeds through the dryer, hot elevator, etc. It included modifications of the plant to reduce the adverse effect of the dryer flame being in direct contact with the crushed hot mix and resultant stack emissions. The second considered the process whereby the recycle mix is introduced into the hot bins, which is often called the Minnesota method.

The pavement to be replaced was a conglomeration of asphalt overlays on top a portland cement concrete pavement. The pavement structure dates back to the 1930's with asphalt overlays--totaling 5½ inches--being added periodically since then. Various depths and asphalt types made up the recycled pavement structure.

As a result of problems in producing the plant mix material, the project suffered several setbacks. In using the method by introducing the recycle mix into the cold feed, residual asphalt and minus 200 mesh material in the crushed pavement were sticking to the dryer and being drawn into the primary dust collector. Because this buildup had to be removed, along with slow removal of the material from the roadway and trying to eliminate a blue smoke emission, production was very slow and the project was temporarily terminated for reassessment.

After evaluating pavement removal procedures (which resulted in switching from Pettibone and Galion pulverizers to a ripper then crush the material) and plant modifications (using the heat transfer method by introducing the crushed pavement material directly to the heated virgin aggregate), the project was resumed in the spring of 1977 and better results were obtained.

I'm not able to cover all the project details at this time, but the cost analysis revealed that with all the problems the cost of the recycled material was $19.46/ton and a new pavement overlay would have been $13.44/ton. The cost of a new conveyor for plant modifications added $4.71 to the recycle mix.

Although this project is not truly indicative of the potential cost savings of recycling, it is a good example of the growing pains the highway community must endure to develop much needed technology.

The fifth project is a hot recycling project in Kossuth County, Iowa (6). The project was 10 miles in length and constructed in summer and fall of 1976.

The contract called for scarifying and removing 7½ inches of bituminous material. The 7½ inches included a 3 inch bituminous treated aggregate base and 2 inch asphalt concrete base course both applied in 1961 and 2½ inches of asphalt concrete base constructed in 1964. After hot mix recycling using a 2/3 recycled mix and 1/3 new materials ratio, a 6 inch depth pavement was to be replaced. The subbase was reworked to accommodate the new pavement. The contract was part of a four project recycling package. The contractor overran the entire project by two weeks. The amount of recycled mix produced for the Kossuth County project was 42,129 tons and there were 82,000 tons produced for all four projects. 5¼ percent asphalt cement was required compared to 7½ percent required for all new materials.

The cost analyses revealed that the recycled mix cost $17.30/ton as compared to $20.59/ton for new materials, a $3.29/ton savings. Other savings included 171,825 gallons of gasoline and 948 tons of asphalt cement. No aggregate savings was given.

The sixth project is Contract No 03-205404 west of Gold Run, California, in Placer and Nevada Counties (7). The total length of the project was 24.5 miles. The project, which consisted of recycling the asphalt concrete shoulders and ramps, was constructed in the summer and fall of 1978. The project is located in the snow belt of the Sierra Nevada Mountains at an elevation of about 3,000 feet at the lower (west) end and 5,000 feet at the upper (east) end. The pavement is subjected to air temperatures of from 10°F$\pm$ in the winter and 90°F$\pm$ during the summer. The mean annual snowfall within the limits of this job varies from 24"$\pm$ at the west end to 200"$\pm$ at the east end.

The shoulder section consisted of 3 inches of asphalt cement, 6 inches of cement treated base, and 15 inches of aggregate subbase. The ramp pavement section was 3 inch asphalt concrete, 9 inch asphalt base, and 12 inches of aggregate subbase.

Approximately 1 inch of the shoulder and ramp surfaces were Roto-Milled. This material was used in a 50-50 blend for recycling.

In addition to the 1 inch asphalt concrete removed, a 4-foot wide section adjacent to the PCC pavement was milled another 3 inches. This 4 inch "trench" was backfilled using the recycled mix, then the entire shoulders and ramp were overlaid with 0.1 inches recycled mix.

The cost analysis for this project showed the recycled mix cost $12.91/ton with using 3.5 percent new asphalt cement and a 50/50 blend mix. The cost of using virgin materials would have cost $16.81/ton with a 6 percent asphalt cement content. A total of $169.000 was saved for the 43,365 tons of recycled AC placed on this project.

As I previously mentioned, all of the individual projects I briefly discussed along with many more recycling projects are documented in report form and these can be obtained through FHWA's Region 15 Office in Arlington, Virginia.

On a statewide basis, the State of Wisconsin has done recent cost comparisons on the project cost of recycled mixes (50/50 ratio) vs. non-recycled mixes. According to data published by Wisconsin in March of this year (shown on slide No. 16), there was a savings of $4.30 per ton. This cost savings was derived from six nonrecycled projects averaging 34,000 tons of mix per project and seven recycled projects which averaged 37,000 tons. The average bid price per ton excluding asphalt cement was $7.60/ton for the nonrecycled mixes and $6.20/ton for the recycled mixes for a $1.30/ton savings. The nonrecycled mixes had an average of 5.9 percent of asphalt cement added compared to 3.6 percent for the recycled mixes. The asphalt cement cost per ton of total mix was $7.50 for nonrecycled vs. $4.60 for recycled--a savings of $2.90. This all equates to a total bituminous mix cost of $15.10 for nonrecycled mixes and $10.80 for recycled mixes, or the $4.30/ton savings.

In conclusion, I have shown cost data from several projects using various construction methods. The State highway departments and FHWA research that went into these projects and many others has revealed that recycling of asphalt pavements can be a cost effective alternative that needs to be considered when asphalt pavement rehabilitation is necessary. Obviously, certain factors such as material and equipment availability, haul distances, etc., come into play when determining cost-effectiveness, but the highway community has shown that asphalt pavement recycling is here to stay.

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SEMINAR ON ASPHALT PAVEMENT RECYCLING
OVERVIEW OF PROJECT SELECTION

Fred N. Finn, P. E.

Project selection is the first necessary step to asphalt pavement recycling. This paper attempts to discuss the primary considerations necessary for a project selection which favors recycling. Such factors as pavement condition, economics, energy, contractor availability, selective rehabilitation, and engineering considerations are discussed. It is concluded that virtually all asphalt construction can be eligible for the use of recycled materials including new construction, reconstruction, resurfacing, restoration and rehabilitation. There are some obstacles which are causing recycling not to be considered as often as it should; for example, a lack of contractors with equipment and experience, and a concern for unverified engineering criteria. The major potential benefits of cost and energy are judged to be sufficiently compelling to justify some additional effort in design and construction to select one of several recycling alternatives, even though engineering and life cycle information is not fully documented. Research and information from demonstration projects indicate that material durability and structural capacity of recycled materials are comparable to new construction, and therefore, should not be a deterrent to project selection. An increase in contractor availability will occur if contractors can be assured of a continuing demand for recycling projects. Public agencies will need to take a leadership role in assuring that long term plans call for recycling of asphalt pavements as a major objective in pavement construction. This paper concludes that recycling procedures are available for a wide selection of projects and that engineers, contractors, and public agencies have a responsibility to promote recycling as a viable alternative for pavement construction and to support studies designed to verify needed engineering and construction criteria.

Asphalt pavement recycling would appear to be an idea or concept whose "time has come." In spite of this, the rate at which technology is being developed and contracts are being advertised appears to be relatively slow.

An analogy could be made to the current health craze taking place in the United States at the present time. The number of people who are exercising regularly has increased tremendously during the past several years; however, translated into the percentage of the total eligible population the number would be small.

Asphalt pavement recycling is not new. Some forms of recycling were used in California in 1952 on airfield construction for the U. S. Navy. The procedures at that time were somewhat primitive and equipment wear and tear in pulverizing old asphalt concrete was considered excessive and costly. Since that time metals and equipment have improved, and productivity has increased to a degree that recycling of asphalt concrete by a variety of procedures is increasingly attractive to the engineer and should be even more attractive to those people responsible for selecting construction alternatives.

Epps, et al (1) provide some compelling reasons for recycling including (1) conservation of aggregate, (2) conservation of asphalt, (3) conservation of energy, (4) environmental preservation; e.g. reduced mining for new aggregate and (5) selective rehabilitation; e.g. elimination of need for full width overlays on multi-laned highways. With all of these advantages, why do we see such a slow evolution toward asphalt pavement recycling, compared to other developments, such as the use of dryer-drum asphalt plants?

The nature of new developments in the highway industry often follows an almost predictable pattern; enthusiastic acceptance followed by diminishing interest based on isolated failures or less than spectacular benefits.

In any new development there are surely going to be some setbacks. Problems not anticipated will occur that will require some adjustments in the process. This should not be cause for abandonment of the procedure if the potential benefits are of significant importance. Remember that much of our engineering technology has been developed empirically; i.e. based on experience and that includes some premature failures.

The U. S. public is always looking for the spectacular fast result; no trial and errors, just results. U. S. engineers are no different; we always want spectacular benefits. For example, a five percent savings in cost may not be sufficient to justify the additional effort and risk associated with a new idea of procedure. However, if the long term benefits or needs can be identified, the economic benefits can be zero or even negative during the early stages of development.

In my opinion as a consultant, who deals with a variety of public agencies, we have very little choice but to move ahead with the use of pavement recycling procedures. The traditional choice of using all new materials is no longer a viable alternative. Somehow we must convince the decision maker to make the choice for recycling. In order for contractors to invest in special equipment and to train personnel, he needs to know that recycling is going to be a long range development with a significant amount of work expected in the future. Such an environment is necessary in order to create the competitive situation so necessary to the full exploitation of the recycling concept.

The success of any pavement design and construction process is first one of selection. Thus, the topic assigned to me is to review project selection procedures. I have elected to discuss some of the pros and cons of recycling. In this sense, cons are really some of the obstacles in the way of recycling as differentiated from the negative considerations. There are really no negative considerations; however, there are some obstacles.

The apporach I have used in gathering information involves three sources; (1) literature, (2) discussions with federal, state, county and city officials and (3) my own experience and judgement applied to project selection for recycling.

The topics which I have selected for discussion pertinent to selection include:

1. Pavement condition
2. Contractor availability
3. Cost and energy comparisons
4. Environmental regulations
5. Engineering technology

Several of these topics will be covered in more detail by other speakers at this conference; however, this overview should serve as an introduction followed by more in-depth development.

Pavement Condition

One of the first decisions necessary in selecting a project for possible recycling is the condition of the pavement. For asphalt pavements, the need for resurfacing, restoration and rehabilitation or even reconstruction, is usually brought about by one or more of the following pavement deficiencies:

(1) Pavement roughness
(2) Excessive cracking of the asphalt concrete
(3) Excessive rutting in the wheel paths
(4) Low surface coefficient of friction
(5) Surface wear (raveling)
(6) Inadequate structure
(7) Inadequate traffic capacity

The subject of inadequate structure will be discussed further under engineering considerations. Inadequate traffic capacity can be cause for rehabilitation or reconstruction particularly if it is anticipated that truck volumes and weight will increase significantly. Inadequate traffic capacity will not be discussed further in this presentation.

The use of recycled material for new construction will be discussed under engineering considerations.

I believe that some type of recycling (surface, in-place or central plant mix) can be used to accomodate any of the first six deficiencies enumerated previously.

For purposes of this discussion recycling procedures include surface, in-place and central plant mix, essentially as defined by Epps et al in reference 1.

Surface recycling - Reworking and/or removal of the surface of a pavement to a depth of approximately 1 inch by heater-planer, heater scarifier, hot milling, cold milling or cold planing devices. The operation may involve the use of new materials (or recycled materials) including aggregates, modifiers and/or asphalt concrete.

In-place recycling, surface and base - In-place pulverization to a depth greater than 1 inch followed by reshaping and compaction.

Central plant recycling - Removal of the pavement from the roadway after or prior to pulverization, processing of material with or without the addition of a modifier, followed by laydown and compaction to the desired grade (and depth).

Pavement roughness in most cases can be corrected by surface profiling, by cold milling, or heater planing, combined with resurfacing, using recycled hot or cold mixes.

Specific criteria for selection of recycling procedures are provided by Epps et al (1).

Excessive cracking can be corrected by several of the available recycling procedures.

The Arizona DOT is one of the few agencies which has tentative guidelines for selection of recycling procedures related to surface cracking. A cracking index has been developed by Arizona which provides a systematic procedure for identification of the extent and severity of cracking (2). Based on this procedure, surface recycling is considered appropriate when the cracking index is 10 percent or more, and more extensive recycling; e.g. in-place or central plant mix, when the index is 40 percent or more.

Epps et al (1) have also provided guidelines for selection of recycling alternatives as a function of type and extent of cracking. Such recommendations include all three recycling techniques; i.e. surface, in-place and central plant mix recycling.

In the case of physical distress (cracking or rutting) it may be advisable to conduct an engineering investigation to evaluate the possible need for structural reinforcement.

Excessive rutting can generally be corrected by surface planing or milling in combination with a surface treatment or thin overlay. The thin overlay could be produced from a combination of recycled and virgin material on roads of medium and low traffic; e.g. less than 5000 vehicles per day.

In some cases surface recycling may not be sufficient to correct problems in the base or subbase, in which case in-place or central plant mix may be the proper option.

Low skid number can be corrected with surface planing or recycling with a minimum of new materials. In extreme cases central plant mix recycling with some percentage of virgin non-polishing aggregate may be required.

Severe raveling can be corrected without recycling in many cases. However, for heavily trafficked highways, surface recycling, with new or recycled materials added, may provide cost efficient benefits.

Inadequate pavement structure can be corrected by increasing the depth of stabilization by means of in-place or central plant-mix recycling. In effect, this is increasing the structural number by increasing the depth of the stabilized layers. If necessary, a new wearing surface can be added as a precaution against accelerated surface wear. It would not be necessary to increase the elevation of the finished pavement if central plant mix recycling were used or if special provisions were made in connection with in-place recycling.

In summary, the range of alternative recycling procedures can be used to correct any deficiency that can be corrected by the use of new materials. This should not be construed as indicating there are no problems associated with recycling. There are some problems, but in concept the techniques are applicable to the full spectrum of design and construction, including rehabilitation.

There may be some skepticism as regards the use of recycled materials for overlay or as a wearing surface. However, as will be discussed, there is no engineering justification for such concern. Experience may prove otherwise, and some caution will need to be exercised in project selection for thin (one course) overlays or as a wearing surface. One recommendation would be to use recycled materials as a wearing surface only for pavements subjected to less than 5000 vehicles per day. Eventually, this limit could be increased.

Contractor Availability

In order to select a recycling alternative for a specific project, the engineer or agency needs to be sure that there are contractors in the area who are prepared to bid on the project. Contractor availability is a necessary consideration in project selection.

In general, contractors are available for surface recycling. The equipment is portable and can be moved over large distances quickly. As the volume of work increases, contractors can station more equipment in central locations and provide more competition in all areas. Also, a range of equipment, for large or small projects, and using hot or cold procedures, is available.

Contractors with the proper type of equipment for in-place recycling are somewhat more limited when compared with surface recycling; however, it is available. In-place mixing has been a standard operating technique in pavement construction and material stabilization for many years. These techniques have been perfected with new materials and can be perfected for recycling.

A recent experience in Walnut Creek, California points out the difficulty that can occur on relatively small projects. The project was designed to recycle the asphalt concrete surface and base by stabilization with cement, plus a new wearing surface; a procedure used on selected projects by Caltrans and Nevada DOT (3). The project was two lanes of a four lane highway, approximately 0.6 miles in length. Only one contractor bid on the project. An award was made in order to correct some aggrevated distress. However, it developed that the contractor did not have the proper equipment, as referenced in the specifications, and the contract was cancelled and subsequently awarded using a more conventional design.

It is believed that if more agencies in the area would specify in-place recycling, contractors would acquire the equipment which would create a more competitive situation.

If the project is sufficiently large the contractor can afford to bring in the proper equipment. The experience reported by E. Aguirre (4) of Victorville, California is such an example. In this case a $100,000 savings was reported by in-place recycling of two miles of city streets.

In many parts of the country the availability of contractors for central plant-mix recycling is very limited except for large projects. In the San Francisco Bay Area (nine counties) there is only one contractor who has acquired equipment especially designed for recycling. In Northern California there are only two contractors with plants designed or modified for use with recycled materials. In Los Angeles one contractor has retrofitted his batch plant to do recycling using the Minnesota process. However, in neither case are agencies beating a path to their door with projects selected for use of recycled materials. The Los Angeles contractor has had two recycling projects in three years. The San Francisco contractor has furnished 4000 tons in two years, all on private works. In Los Angeles the contractor offered a one dollar rebate on all recycled materials and could find no takers.

Contractors face a "Catch 22" situation with regard to spending money for equipment required for recycling. Before they can invest, they need to have some assurance that the specifying agencies will follow a long range plan requiring or allowing the use of recycled materials. However, specifying agencies are reluctant to use recycled materials unless there are a number of contractors in the vicinity who are properly equipped and who have experience in processing recycled materials.

In summary, contractors for surface recycling are available in most parts of the United States and competitive conditions exist in many cases. However, availability of contractors for in-place and central plant recycling is somewhat limited by the size of the project.

To improve the contractor availability situation, action will be required on the part of the larger agencies; e.g. federal, state and larger counties and cities. These agencies will need to take the leadership in establishing a continuing market for recycled materials.

Cost and Energy

Cost is the traditional criteria for selection between various design and rehabilitation alternatives. The alternative with the least cost, including initial and maintenance, is usually elected by the designer. Another consideration which may or may not be reflected by comparative cost is energy. Both of these subjects will be presented by another author at this seminar. However, a few comments may be appropriate in this overview.

Alternative bid prices for three projects in Arizona (I-10-4/68, I-17-1/25, I-40-2/86) indicate that comparative prices between recycled asphalt concrete and new asphalt concrete would result in a savings of $0.43 per ton in favor of the new asphalt concrete or a difference of 2 percent.

Considering that bid prices do not always reflect actual costs, this comparison does not correctly reflect the potential benefits between the two techniques.

In Hawaii a project involving 15900 tons of asphalt concrete was modified by change order from all new to 30 percent recycled material, and the price was reduced by $0.80 per ton or 3 percent.

In California, four projects were analyzed which showed substantial savings as summarized below:

Project	Recycled Aggregate		Cost/Ton New	Recycled
I-80 (Gold Run)	50%		$16.81	$12.91
I-5 (Weed)	50%		$29.59	$20.09
SR 395 (Bishop)	100%		$22.66	$20.35
I-10 (Blythe)	55%		$22.08	$13.39
		Average	$22.78	$16.68

The total savings in dollars were estimated to be $761,500 with an average reduction of 26 percent in the asphalt requirement.

Discussions with one materials supplier, who does no laydown, indicates that the potential savings in using recycled mixes is $3.00 per ton, or 17 percent. In this case the contractor is using all cold millings, no crushing, which cost between $1.25 and $2.25 per ton delivered to his yard from projects within a 20 mile radius of his plant. Virgin aggregate costs the contractor $4.00 per ton.

Local dumps are charging $70 per load for dumping street rubble including asphalt concrete. Some contractors are now accumulating asphalt concrete for recycling by allowing contractors to dump materials in their yard at no cost. At this price, the contractor can afford to haul the material a considerable distance and still be economically ahead of dumping.

Thus, the economic benefits are there. Even in Arizona it is believed the benefits are real although the method of bidding may in some way disguise these benefits. Also, haul distances and plant location will have an effect on cost comparisons.

Economics on a particular project can also be affected by selling salvaged materials to contractors. For example, the salvaged materials can be retained by the agency or credited to the project by the contractor.

If the salvaged materials are to be retained by the agency, the contractor would be paid to remove, process (as specified) and deposit at a site designated by the agency which would be convenient for future applications. For example, the material could be hauled to the maintenance yard where it would be used for patching, tranch backfill or shoulder repairs. In this sense the material has value which should be credited to the job and to the process.

If the salvaged material is retained by the contractor, the bids should reflect the fact that he has retained all or some part of the salvage material.

The one area that can produce a real benefit is in energy savings. For example, the I-10-4(68) project in Arizona shows a savings equivalent to 19,400 gallons of gasoline for a project involving 57,500 tons of asphalt concrete or one-third of a gallon for each ton of mix. On the project the savings in BTU/ton amounted to 11 percent.

Peters et al (5) have summarized typical energy comparisons, including transportation, for new and recycled asphalt concrete. Based on their assumptions a typical energy requirement for new asphalt concrete would be 432,300 BTU/ton and for recycled asphalt concrete the value is 327,992 BTU/ton or a 24 percent reduction in energy.

Factors included were (1) manufacture of asphalt cement, (2) hauling asphalt cement, (3) crushing gravel, (4) haul salvaged A.C. to miles, (5) crushing salvaged material, (6) drying and heating materials, (7) hauling, spreading and compacting either type mix.

With some justification, many engineers believe that the benefits in energy savings will be reflected in energy costs. This would be the traditional approach; however, it may be time to examine that approach.

Is the real value of energy savings reflected in cost savings? An analogy can be made with water. Does the cost of water reflect the value of water? We need to conserve water because it is precious and not in ever increasing supply. For project selection some credit or value needs to be given to the energy savings which is not necessarily reflected in cost. I have no specific recommendation to make except to suggest that more sophisticated evaluations are necessary which go beyond standard economic comparisons.

Regulations

One possible concern for the use of recycling procedures is government regulations; specifically, requirements related to safety, noise and air pollution.

Of these three, the only one that appears to be significant is air pollution and particularly opacity requirements associated with central plant mix requirements. This problem has not yet been satisfactorily resolved (6). The current solution is to spray water on the cold feed materials, to increase the amount of virgin material or decrease plant production. None of these is entirely acceptable and each tends to increase the cost of construction using recycling procedures.

Some modifications in equipment have helped to reduce the air pollution problem; however, the general solution is to reduce the amount of virgin aggregate used in the mix. An upper limit of 60 percent recycled material is the figure most frequently quoted. This is not ideal; 100 percent recycled would be preferable. However, the surplus can be used for new or reconstruction projects or for strengthening existing projects by in-depth stabilization.

Engineering Considerations

Project selection can be divided into two catagories; (1) surface recycling and (2) in-place or central plant-mix recycling. If the project can be restored by corrections to the surface with a minimum of new materials, surface recycling will prove satisfactory. If substantial corrections are required, more extensive actions will be necessary which can be achieved by in-place or central plant mixed procedures. Some of the major advantages and disadvantages are enumerated in Table 1.

Specific engineering considerations or design parameters which will influence project selection are:

1. Mix design
2. Durability of recycled mixture
3. Structural properties
4. Construction uniformity

A detailed discussion of these items is beyond the scope of this report; however, some summary remarks are pertinent.

Table 1

Advantages and Disadvantages of Recycling Asphalt Pavements

Recycling Procedure	Advantages	Disadvantages
Surface Recycling	1. Reduces reflection cracking	1. Limited structural improvement
	2. Promotes bond between old pavement and recycled material	2. Potential air pollution problems (dust, smoke)
	3. Reduces tendancy for raveling at conforms	
	4. Corrects a variety of distress types at all levels of severity	
	5. Selective rehabilitation	
In-place Recycling	1. Significant structural improvements	1. Problems of quality control
	2. Corrects all distress types at all levels of severity	2. Some design parameters unknown
	3. Selective rehabilitation	
Central-plant Recycling	1. Designed improvement in structural capacity	1. Improved quality control required
	2. Corrects all distress types at all levels of severity	2. Some design parameters of questionable reliability
	3. Improved quality control over surface and in-place recycling	3. Potential air pollution problems
	4. Selective rehabilitation	

Mixture Design

The elements of mixture design have been rather thoroughly researched and summarized in the literature (1, 3, 7, 8, 9). Basically, the mix design approach used by investigators is to produce a mixture which meets all standard material specifications for the type of mix being produced.

The mix design procedure proposed by Kari et al (9) and which is generally representative of procedures proposed by others is summarized in Table 2.

Table 2

Recycle Mix Design Process

1. Evaluate salvaged material
   . gradation
   . amount and consistency of asphalt
2. Establish consistency requirements for recycled material
3. Determine proportions of recycling agent; i.e. low viscosity asphalt or special petroleum derivative, required to provide desired consistency.
4. Determine proportions of recycled material, recycling agent and virgin aggregate necessary for stability and other mix design requirements, including water susceptibility, by appropriate laboratory procedures.

Once the appropriate proportions are determined for a range of percentage of virgin aggregate, the mixture design is ready for field trials.

All available information indicates that recycled mixtures should be equivalent to new asphalt concrete (1) and would be suitable for all types of construction including surface recycling, in-place or central plant mix applications.

Durability of Recycled Mixtures

Based on laboratory evaluations (1, 6, 7, 8) the durability properties of the asphalt in recycled mixtures should be equivalent to that of conventional asphalt concrete. Only time will tell if the traditional tests used to evaluate asphalt durability will apply to recycled materials. At the present time there is no reason to suggest they will not. More research is needed to confirm this assumption.

Structural Properties

For in-place and central plant mix recycling it will be necessary to establish coefficients appropriate for both structural enhancement by increasing the thickness of the stabilized layers and for overlays.

Epps, Little et al (1) summarize extensive studies made to evaluate the structural properties of recycled materials. The procedure used to make such comparisons was largely by means of computer simulation using recognized mechanistic procedures. Some effort was made to incorporate AASHO Road Test Data into their analysis in-so-far as it was applicable to the procedures used. Also, a number of field projects were included in the study by means of core sampling, testing, and dynaflect measurements.

The conclusions reported in Volume 1 of reference 1 are summarized as follows:

1. Based on a structural evaluation, recycled asphalt concrete bases stabilized with either asphalt emulsion, cutback, cement, lime, or with the addition of an asphalt modifier are superior to aggregate bases in terms of load distribution.
2. Recycled bases in this study are structurally equivalent to or superior to conventional stabilized bases.
3. Although there was considerable variability in results, the in-situ properties as determined from an analysis of dynaflect measurements, are comparable with properties of conventional materials. It can be concluded that overlay designs would not be affected by the use of recycled materials.

In summary, project selection would not be affected by structural differences associated with the load distribution or performance properties of recycled materials.

These conclusions should be considered somewhat tentative. However, the information is sufficiently conclusive to justify using conventional design parameters for project selection.

Selective Design Alternatives

Arizona DOT has pioneered a design procedure which combines recycling procedures (5). Specifically, for multi-laned highways, ADOT has designed several projects with surface recycling and thin overlay in the passing lane, and for central plant mix recycling in the truck lane, also with an overlay. The procedure takes full advantage of various recycling combinations in order to minimize the overall cost.

The selective use of heater scarification and overlays on an as-needed basis has also been used by ADOT to maximize the benefits of recycling.

Construction Uniformity

One of the major concerns of engineers with regard to the use of recycled materials is construction control.

Quality control of construction is important whether it be for all new construction or recycling. Because of non-uniformity of salvaged materials, or handling techniques, uniformity may be somewhat more of a problem in recycling than it would be in conventional materials. Some additional attention will need to be given to monitoring recycling projects to assure uniformity.

Summary

In the preceeding sections of this report a brief discussion has been presented concerning selection of projects for asphalt pavement recycling. Based on the information available it would seem reasonable to conclude that recycling procedures are an acceptable alternative for all types of design including new construction, resurfacing, restoration and rehabilitation.

Some additional engineering effort will be required in connection with mix design and construction control. The potential benefits in cost and energy should easily justify the additional effort required.

Unfortunately, in the absence of contractor capability, there appears to be some reluctance to establish a long-range policy to implement recycling as an alternative for every construction project. Contractors need that reassurance before they can acquire for themselves the proper equipment and experience necessary to improve their capability.

There is a need for technical literature for use with recycling projects. Reference 1 is a significant beginning to meet this need. However, additional mix design guidelines are needed and most specifically, model specifications and construction control requirements need to be put in the hands of public agencies and consulting engineers.

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COST AND ENERGY CONSIDERATIONS IN PROJECT SELECTION FOR RECYCLING ASPHALT PAVEMENTS

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This report discusses the costs and energy factors involved in various recycling techniques and compares such costs and energy use with those involved in conventional procedures using all new materials for the rehabilitation of asphalt pavements. It is emphasized that the relative amounts of transportation and construction energy consumed in alternative procedures are of primary concern in highway construction and maintenance, and that this factor controls to a considerable extent the relative costs of different alternatives. The energy savings and cost reductions reported for the recycling projects included as a part of Federal Highway Administration Demonstration Project 39 are summarized. Differences in theoretical transportation and construction energy requirements for usual overlays and for hot recycling through a central mixing plant are also shown. The general conclusions drawn are that a number of recycling techniques offer means for conserving significant amounts of energy and reducing costs over traditional ways of rehabilitation. The amount of energy saved and the reduction in costs will depend on the conditions of each project. On-site cold recycling offers the greatest potential for direct energy conservation, but more information is needed on the durability of recycled components before the lifetime cost and energy effectiveness can be known.

Most reports concerning the feasibility of recycling asphalt pavements point out that the individual factors surrounding each project determine whether or not such recycling is economical or conserves energy. Where central plant mixing is involved the various factors interact in different ways depending on the distance between the source of new materials and the mixing plant or the distance from the job site to the mixing plant. Relative time and traffic delays are also factors in urban and congested areas. Traditionally, the cost-effectiveness has been recognized as the most desirable criterion by which to judge the selection of alternatives. More recently, some engineers and administrators have suggested that energy-effectiveness might be a better alternative. Under normal circumstances, however, the two alternatives will lead to the same conclusions.

There is a close relationship between overall energy requirements and costs. In particular, the recent very large increase in cost for construction of asphaltic highways is related to the increase in the cost of petroleum based fuels and asphalt, a derivative of petroleum. While it is not difficult to judge the amount and cost of energy consumed in the operation of equipment, some of the indirect energy balances are very difficult to determine and there has not been universal agreement on the energy factors involved in a number of operations. Additionally, the relative cost-effectiveness of two alternative materials or construction procedures for highways may not always be easy to determine, since the years of adequate performance that will be provided by each alternative cannot be precisely predicted. When dealing with recycling concepts, the economic value of conserving raw materials and the value of eliminating potential environmental problems are also somewhat intangible but must be considered in determining overall cost-effectiveness.

Although other factors may influence the final decision, the first factor to be considered in deciding whether or not a given recycling alternative is desirable is its cost relative to those of established rehabilitation procedures. The various reports prepared as a part of Demonstration Project No. 39 conducted by the Federal Highway Administration (FHWA) in cooperation with a number of states contain cost and energy use comparisons for a number of alternatives.(11) Although the comparisons within the various projects are not always made on the same basis, they generally show recycling to cost less and to use less energy than other available alternatives. While the final evaluation of cost-effectiveness must await information on how long the recycled pavements provide adequate service, these reports strongly support the feasibility of the recycling option in a number of different situations. However, much remains to be done to establish recycling as an alternative that is automatically considered in all situations. In a discussion at the FHWA Research Project Review in Williamsburg, Dr. Richard Smith stated:

"The technology to recycle reclaimed asphalt pavement materials has been developed, but little use is being made of it. The principal reason is seen to be a lack of economic motivation as the cost savings to be gained by recycling remain obscure to highway administrators and asphalt contractors alike." (2)

In the same presentation Dr. Smith pointed out the increasing value of salvageable material. In particular, recycling operations that reduce the need for new asphaltic binder are becoming increasingly attractive as the price of asphalt increases. When asphalt sold for $33 a tonne ($30 a ton) a 4% reduction in the amount of asphalt needed for a new mix amounted to $1.33 a tonne ($1.20 per ton); but at $165 a tonne ($150 a ton) for asphalt, a 4% reduction is equivalent to $6.61 per tonne ($6.00 per ton), a significant difference.

Energy Classification

In considering the energy used for any project, there is a need to include more than the total energy expressed as Btu's or an equivalent number of gallons of diesel fuel or gasoline.

As has been pointed out, "All Btu's were not created equal". It can also be added that "all Btu's are not interchangeable". (3) Someone has calculated that the American public carries around 1 billion kg (2.3 billion lb.) of excess weight. The extra food calories and the energy required to produce that food are sufficient to operate 900,000 average U.S. autos for a year — or to supply the annual residential electrical demands of Boston, Chicago, San Francisco, and Washington, D.C. Such calculations supply interesting trivia for conversation but they have no true bearing on energy conservation. There is no way that Btu's saved by a reduction in the human intake of food calories can be economically converted to either vehicle fuel or electricity.

In evaluating the energy impact of highway construction four categories of energy should be considered. These have been defined as follows:

1. Embodied Energy: The amount of energy that has been used to manufacture or process a material up to the point it is to be used for a project.
2. Transport Energy: The energy needed to move material from the point of manufacture or final processing to the job site or the plant at which it is to be used. Primarily, this is the fuel required to operate loading, hauling, and unloading equipment.
3. Construction Energy: The energy needed to process the material, move it to the job site, and complete the project. For asphalt used in highway construction this category includes energy to heat and dry the aggregate, operate the plant, haul the mix to the job site, place it on the roadway, and compact it.
4. Indirect Energy: The energy used by the work force in getting to and from the job site, the increased energy expended by users of the highway because of construction related delays, the energy involved in manufacturing equipment, etc. (3)

Transport and construction energy are the categories of major interest to highway contractors and engineers. These categories consist of the fuel used in hauling materials and in the operation of equipment for processing materials and manufacturing the finished product. Conservation in these categories has a direct bearing on reducing the costs of highway construction or minimizing increases in costs. In considering recycling and alternative rehabilitative procedures, the differences in energy use in these categories will likely be one of the major considerations in determining relative costs.

For manufactured products such as metal components, the relative amount of embodied energy will likely be reflected in costs. However, this may not be true for those natural resources such as aggregate and asphalt that are processed rather than manufactured. In particular, for the construction of asphaltic pavements the amount of this category of energy used depends on how embodied energy is defined.

Under one view embodied energy includes the Btu's in the asphalt itself, since that amount of energy was originally considered a part of the available energy in the petroleum from which it was refined. Under another definition, which is endorsed by the Asphalt Institute and others, the asphalt is considered to be a construction material that is removed from petroleum by the refining process; therefore, they count only the prorated share of the refining energy as manufacturing or embodied energy. Still others consider the Btu's in the asphalt as not being used up, but as being stored in the highway. In another view high sulfur asphalt would be classed as a waste by-product of the refining process — in which case the embodied energy would include only the energy used in processing and storing asphalt cement for sale.

Under present circumstances the differences in these views may be of only academic interest to the highway builder, because engineering factors along with the availability and costs of materials form the basis of his decision as to whether asphalt or some suitable alternative will be used for a given project. However, if proposed revisions in FHWA regulations go into effect, the definition of embodied energy could become very important. The proposed changes would, in effect, require an evaluation of the energy impact as part of the environmental impact statement. It is possible that decisions concerning alternative types of construction could be affected by their relative energy efficiencies. As many realize, when the Btu's in the asphalt is considered to be embodied energy, asphalt paving becomes substantially more energy-intensive than portland cement concrete paving. When the Btu's in the asphalt are not included as embodied energy, asphalt construction is placed in a much more favorable light.

This difference in definitions should not be allowed to influence the selection of pavement type. It is important that the present practice of judging alternative types of construction on the basis of technological considerations, availability, and cost-effectiveness be continued. It is also important that changes in refining processes and techniques for burning residual petroleum fuel be monitored by the highway industry to assure that an adequate supply of asphalt for highway construction and maintenance is available. Under present circumstances, the generally large amount of residual fuel available and the difficulty of burning some residuals containing asphalt assure adequate supplies of asphalt for highway construction. However, future developments could change refining priorities in a way that would create shortages of asphalt in some locations.

Indirect energy has a bearing on overall land use and transportation planning, but for alternative types of highway construction the amounts required are substantially the same. Consequently, in this discussion, no further consideration will be given to indirect energy.

Recycling Options

The Texas Transportation Institute draft report on "Interim Guidelines for Recycling Pavement Materials" identifies 24 recycling alternatives.(4) Eight of these options involve maintenance and repair operations on pavement surfaces not often associated with recycling. Another 8 involve in-place recycling that results in minor or major structural improvements; they generally involve crushing, pulverizing, and replacing the old pavement with or without new asphalt or modifiers. The final 8 options involve central plant recycling. These may be either cold or hot mix operations with or without the addition of new binder. Obviously, the type of project involved, the location of the project (urban or rural), and the amount of traffic involved automatically rule out certain options for given projects. Because the many combinations of equipment and procedures and the rehabilitative techniques that are available do not provide the same level of performance or length of service before additional measures must be taken, estimates of energy or cost savings for various classes of recycling based on theoretical considerations are so dependent on the assumption made that they are of questionable value. After consideration of a number of these alternatives, it was decided that the information in the reports on work performed as part of FHWA Demonstration Project No. 39 provide the best evidence that recycling enables energy conservative and cost savings in many situations. A summary of the energy and cost analyses presented in the reports on this project is given in Table 1.(1)

The recycling procedures demonstrated varied widely and were undertaken to solve different problems. Also, for different situations essentially the same recycling alternative may be compared to different rehabilitative procedures. In almost all cases, however, the reported savings by recycling are significant. Of the 21 projects reporting energy and cost analyses, only 2 reported negligible savings in energy and 5 reported negligible savings or increased costs for the recycled material; and in each of these cases, special circumstances appear to have influenced the reported cost comparisons. Reported figures for energy conservation, expressed as equivalent gallons of diesel fuel saved for each lane-mile of recycled pavement, varied from a low of 390 gal. to a high of 7,730 (equivalent to a low of 920 ℓ/km to a high of 18,260 ℓ/km). The 70-gal. per lane mile saving in report DP-39-4 was excluded because it represented the removal and reuse of material originally used as a temporary detour rather than a rehabilitation of an old pavement.

The reasons for the very wide spread reported were not completely analyzed, but differences relate primarily to the recycling sequence, the extent to which hot materials were used, and the percentage of recycled materials in the rehabilitated pavement. Cost reductions are not always proportional to energy saved; they are also influenced by the bases of comparisons. In general, the highest reduction of cost is estimated when actual costs for cold, in-place recycling projects are compared to estimates for replacing bases with hot black base and asphalt concrete overlays. Although quantitative estimates of energy and money to be saved by specific procedures cannot be derived from Table 1, it can be concluded that in almost any type of situation recycling will require the consumption of less direct energy in the project and also provide a savings in costs. Whether or not a project is cost-effective or energy-effective cannot be judged from the figures in Table 1, since the level and length of service to be obtained from the recycled material has not been established.

The potential advantages of in-place recycling techniques in several situations where costs must be kept low have been recognized for some time and such techniques are used to a considerable extent. However, until recently, recycling on heavily travelled roadways as an alternative to the usual practice of applying an overlay of all new material has not been considered to a large extent. Consequently, it is important to examine some of the theoretical aspects and basic principles involved in central plant, hot mix recycling and to compare the amount of energy it requires with the energy required in normal overlay procedures.

Figure 1 is a block diagram of the various operations for conventional overlays and for central plant, hot mix recycling. The energy used in each of these operations varies from project to project but factors based on reasonable assumptions are available, and, based on theoretical factors, the relative differences in the amounts of energy consumed can be estimated.

Blocks A-1 and S-1 represent embodied energy — that is, energy already consumed when the highway engineer becomes involved. The level of this energy does not enter directly into the amount of fuel required to build a highway and, since the method of calculating this energy is in question, it will not be further considered in this discussion.

Blocks S2 and R2 are key units, since the distances the materials must be moved are important in establishing potential energy conservation. Energy must also be expended to crush the old pavement and stockpile the crushed material at the dryer. Differences in energy consumption between the overlay and recycled mix will occur from different moisture contents. From this point, the amounts of energy consumed in mixing and hauling the material from the plant to the job site and in compaction are essentially the same for the new overlay and the recycled mix.

To illustrate the effects of the distances that the aggregate must be hauled to the job site and the distances the old pavements must be moved to the plant and returned, calculations of energy used in hauling (transport energy) and energy used in construction (construction energy), were made for several sets of assumed conditions.

All calculations were made using the factors published in "Energy Requirements for Roadway Pavements",(5) with the following assumptions.

Composition of overlay:

Asphalt — 6%, aggregate basis
Aggregate — 85% crushed stone
15% sand

Composition of new mix added with recycled material:

Same as for overlay

For recycled material, add 2% asphalt
Asphalt is hauled 50 miles in 4-axle rigs
Aggregate, reclaimed material, and new mix hauled in 3-axle rigs
New aggregate contains 5% moisture
Reclaimed mix contains 2% moisture
Aggregate and reclaimed mix enters drier at 21°C (70°F)
Final mix heated to 149°C (300°F)

Table 1. Summary of cost and energy savings given in FHWA demonstration project 39 reports.

Report No.	Classification of Pavement Recycled	General Description of Recycling Process	Energy Saved in Equiv. Gal. Diesel Fuel[a]		Estimated Dollar Saving[b]		Remarks
			Total	Per Lane Mile	Total	Per Lane Mile[c]	
1	Rural	Cold. Total pavement ripped, pulverized CMS emulsion added; relaid as 4-in. mat.	11,900	4,000	26,600	6,700	
2	Urban (curb-gutter)	Cold. Top 1 in. heater scarified, old material blended with new a.c. in repaver, HVMS emulsion added as needed, relaid as surface.	0.06 per s.y. -in.	420	Nil	Nil	Cost compared with average bid price of conventional overlay.
3	Interstate	Hot. Top 0.15 ft. milled, material mixed in pugmill with rejuvenators and new mix relaid. Friction course added.	76,200	4,760	320,700	20,000	
4	Material from Detour	Hot. Old material blended with new at hot plant. Laid as 6 in. mat on secondary road.	1,100	70	59,400	4,950	
5	State Road	Cold. Heater scarified, rejuvenator added, compacted. Overlaid with 1 1/2 in. mat.	32,400	1,120	408,300	14,080	Compared with removing pavement, replacing with 2 in. hot mix.
6	State Road	Hot. Top 3 in. cold milled, stockpiled, blended with new material in hot plant, relaid as surface.	9,100	810	Not Reported		
7	U.S.-Secondary	Cold. Top 1 3/4 in. milled, replaced on shoulder.	246,600	5,000	737,600	15,000	Compared with hot mix overlay.
8	Rural	Cold. Top 3 in. scarified, SA-1, and new asphalt added, road mixed, compacted as new base. Overlaid.	Not Reported			23,260	Compared with hot mix base.
9	Interstate	Hot. Total 4 1/2 in. cold milled, blended with new material in hot plant, relaid as surface.	27,200	450	146,000	2,430	
10	Rural	Hot. Pavement scarified, crushed, blended with new material in hot plant, relaid as surface.	154,500	7,730	138,400	6,920	
11	Interstate	Hot. Pavement scarified, crushed, blended with new material in hot plant, relaid as base. Overlaid.	0.21 gal./ton		Not Reported		
12	U.S.-Secondary	Cold. Top 1 1/2 in. heater scarified, new material added, compacted. Open graded surface applied.	113,000	5,280	232,000	10,841	Compared with hot mix overlay.

13	Rural	Cold. Total pavement pulverized, mixed, relaid as base. Two inch overlay applied.	0.48 gal/ ton		None		Recycled base cost more per ton.
14	U.S.-Primary	Hot. Overlay over P.C.C. removed, crushed, blended with new material in hot plant, relaid as surface.	Nil		None		Long haul to crusher and high capital costs for equipment.
16	Interstate	Hot. Total 4 1/2 in. pavement broken up, crushed, remixed at hot plant, relaid as surface.	Nil		Nil		
17	U.S.-Primary	Hot. Total pavement cold milled, blended with new material at hot plant, relaid as surface.	52,200	1,070	Nil		
19	Material from Runway	Hot. Old material stockpiled, crushed, blended with new material at hot plant, relaid as base. Overlaid.	10,700	1,690	59,600	9,370	
20	U.S.-Secondary	Cold. Top 4 in. pulverized, CMS2 added, mixed, relaid as surface.	0.67 gal/ s.y.	4,720	2.21/s.y.	15,560	Compared with new base and overlay.
21	State Road	Cold. Surface heater scarified, compacted, rejuvenator added. New 1 in. overlay applied.	Not Reported		Not Reported		
22	State Road	Cold. SS-1 applied prior to recycling top 1 in. with repaver. Friction course added.	19,200	1,330	85,350	5,930	
23	Urban	Hot. Top 1 in. to 3.5 in. milled, blended with new at hot plant, relaid as leveling course. Overlaid.	5,130	390	26,800	2,040	
24	3-Projects: Interstate, Rural, Secondary	Cold. Pavement ripped, pulverized, aggregate added, relaid as base. Overlaid.	Not Reported		Not Reported		
25	Rural	Cold. Pavement ripped, pulverized, new aggregate added, road-mixed with SS-1h, compacted. Chip seal added.	11,880	2,700	54,000	12,270	Compared with new 4 in. mat.

(a) 1 gal. = 3.78 litres
1 gal/lane mile = 2.36 litres/lane kilometre
(b) Costs of recycled techniques compared with costs of usual rehabilitation procedure.
(c) 1 mile = 1.6 kilometres

Figure 1. Major steps in constructing overlays and in central plant, hot mix recycling.

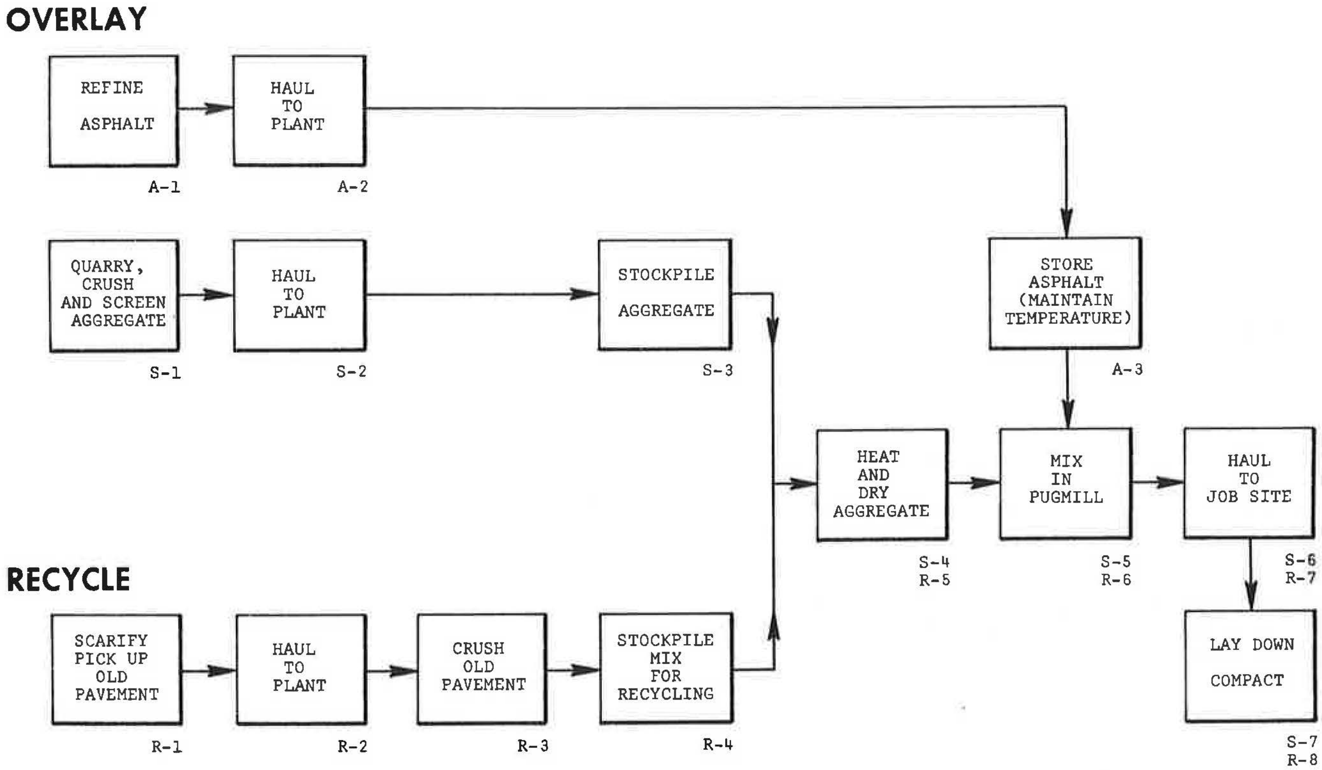


Figure 2 illustrates the combined transport and construction energy used for an overlay compared to that for recycling 50-50 and 80-20 blends of recycled and new material, where the job site is assumed to be an average of 16 km (10 mi.) from the plant and the aggregate must be hauled the distances indicated. This figure demonstrates the significant effect of the transport energy required to haul new aggregate. As the distance the new material must be hauled increases, the advantage of recycling significantly increases, as would be expected. Energy saved also increases as the proportion of recycled material in the final mix increases. For a haul of 96 km (60 mi.) for new aggregate, the energy saved by using a 50-50 blend of recycled and new materials amounts to about 4 ℓ. of diesel fuel per tonne of mix placed (1 gal. per ton). If an 80-20 blend can be used, about 7 ℓ. of diesel fuel per ton of mix placed can be saved (1.7 gal. per ton).

For Figure 3, calculations were made assuming new aggregate was available 16 km (10 mi.) from the plant in one case and 64 km (40 mi.) in a second case. The transport and construction energies were calculated and plotted for various distances from the job to the plant.

As can be seen, the energy advantage of recycling is lost if new aggregate is available near the plant and the material for recycling must be hauled an appreciably greater distance. As shown in Figure 3,when the aggregate must be hauled 16 km (10 mi.) to the plant any haul distance from the plant to the job site that exceeds 35 km (22 mi.) results in a use of more transport and construction energy for recycling than for an all new overlay. When the aggregate is hauled 64 km (40 mi.), recycling retains its advantage until the distance between the job site and the plant exceeds 96 km (50 mi.)

Another significant conclusion to be drawn from these calculations is that a large proportion of the energy used is needed for heating and drying the aggregate or recycled mix. Consequently, if this step can be eliminated, a significant amount of energy could be saved. For the situation in which the aggregate is hauled 16 km (10 mi.) to the plant, and the job site also averages 16 km (10 mi.), the construction energy used for heating and drying the aggregate or mix for a 50-50 blend is 59% of the total. For a 64-km (40-mi.) aggregate haul, this energy amounts to 50% of the total. The use of asphalt rejuvenators in cold procedures offers a means of saving a significant proportion of this energy. On-site preparation also is advantageous because these is no requirement for transport energy.

It thus appears that efforts to improve cold-milling and on-site "repaving" equipment should be continued so as to take maximum advantage of the potential for reducing costs and conserving energy.

Major Consideration for Various Classes of Roadways

The interim guidelines prepared by the Texas Transportation Institute lists four broad classes of roadways.(4) These are:

1. Interstate and urban freeway.
2. Rural primary (U.S. and state signed routes).
3. Rural secondary (farm to market roads, park roads, etc.).
4. Urban streets (arterial collector, local).

Figure 2. Effect of the distance new aggregate must be hauled to plant on energy consumption in central plant recycling.

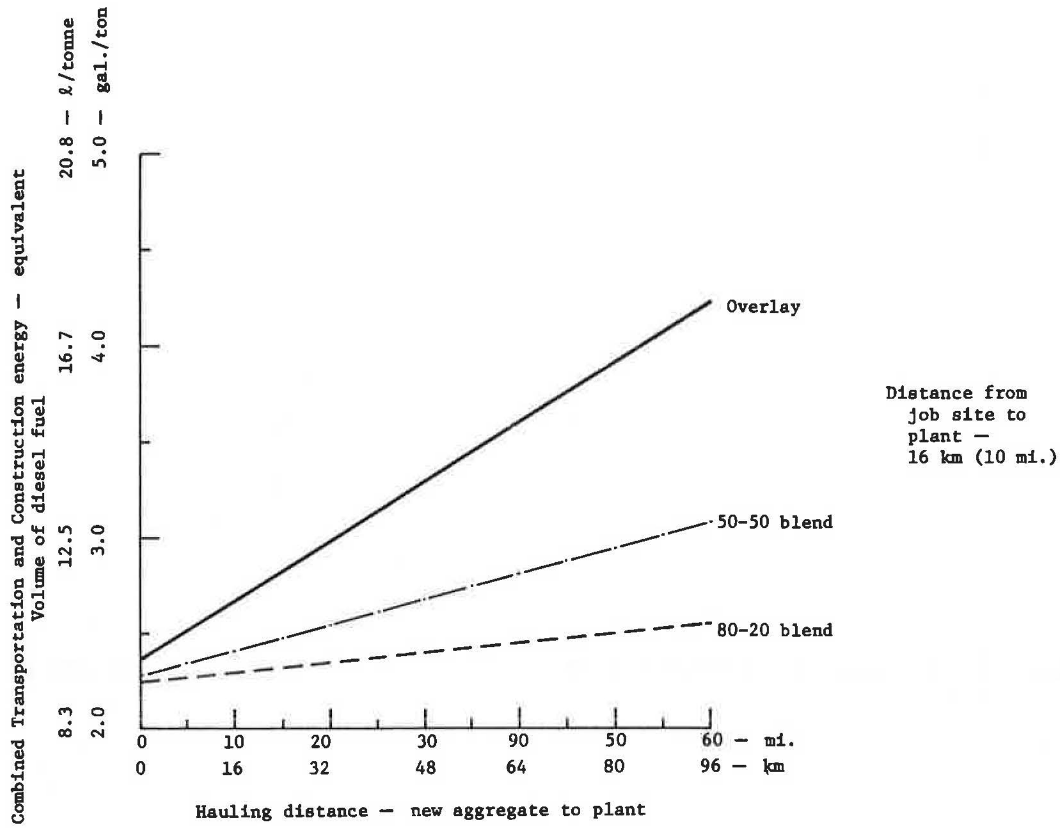
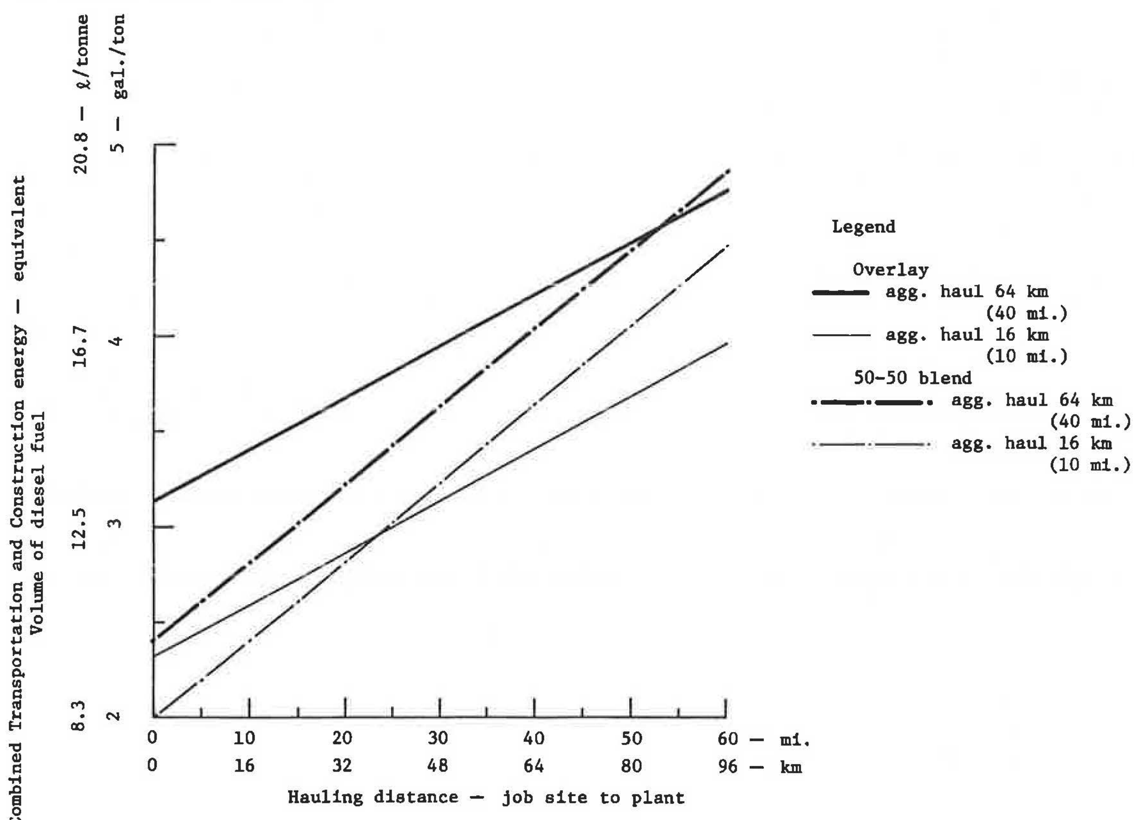


Figure 3. Effect of hauling distance from job site to plant on energy consumption in central plant recycling.



As illustrated by the brief description in Table 1 of the various recycling projects constructed in Demonstration Project 39, there are numerous combinations of treatments for recycling road material and the most desirable process for a given project does not necessarily depend upon the class of roadway. Consequently, it is not possible to pinpoint the specific energy and cost factors that must be considered for each class. However, general statements of the conditions most likely to apply for different classes of roadways may be of some significance.

1. Interstate and Urban Freeway

The usual rehabilitation procedure for this type of highway would be either an overlay after correcting localized base problems or surface unevenness, or complete rebuilding of the roadway where serious base failure has occurred. The most likely recycling technique is to remove all or part of the old pavement and to reuse the removed material as a portion of the new hot mix. The new mix may be applied as a base or surface.

The primary energy and cost consideration is the relationship between the distance from the project to the asphalt plant and the distance that new aggregate must be hauled to the plant. As has been shown, as the distance the aggregate must be hauled becomes progressively greater than the distance between the mixing plant and the job site, the saving in energy and cost for recycling increases significantly. Conversely, when a source of new aggregate is at or near the asphalt plant, the advantages of recycling decrease significantly as the distance between the plant and job site increases. Under conditions favorable to recycling, the higher the percentage of recycled material in the new mix, the greater the savings in energy and costs. However, problems in controlling pollution and the probable lesser performance capabilities of the recycled mix are negative factors. The amount of new asphalt or rejuvenators to be used is also an important consideration.

2. Rural Primary (U.S. and State Signed Routes)

Table 1 indicates that surface recycling is often used for this class of roadway. The more significant energy savings and cost reductions occur when the surface material is milled or heater scarified and reworked on-site with the addition of a rejuvenator or asphalt emulsion. Sometimes, aggregate is also added. Processing through a road mix machine in this application provides through mixing. Hot mixing of the removed material with new aggregate and asphalt at a central plant is also sometimes employed with a lesser conservation of energy because of the fuel needed to heat the material. However, for heavy traffic conditions, the use of the additional energy may be cost-effective and a better blended and more uniform product is obtained.

3. Rural Secondary (Farm to Market Roads, Park Roads)

Recycling of this type pavement often consists of reworking the total pavement and base into a new base with a surface treatment. The significant cost and energy savings in these situations results from the elimination of the need to purchase large quantities of aggregate and transport them to the job site. Obviously, savings increase significantly as the distance the new aggregate must be hauled increases. In-place mixing with road machines or manipulation with graders are most often used on this class of roadway. The use of emulsified asphalt in lieu of cutback asphalts or hot plant mix is the most energy efficient procedure.

4. Urban Streets

Surface recycling with hot plant mixing is likely to be required for urban streets. One significant advantage to recycling in this situation is the elimination of the need for raising levels of manhole covers or correcting the heights of curbs and drains as would be necessary for an overlay. One alternative that may be considered for this class of roadway is to remove and stockpile old surface material for use elsewhere in a less demanding situation as part of a base or surface course. In this situation, the savings in energy and costs are not in the initial project but are realized by salvaging the economic value of the removed material on another project.

Conclusions

The conclusions to be drawn from the information presented in this discussion as well as from indications from other sources, are as follows:

1. Various recycling techniques can be used to save energy and reduce costs in rehabilitating pavements. For each project, the amount of energy saved or the reduction in cost will depend on the prevailing conditions.
2. For highway reconstruction and rehabilitation procedures, the more important energy considerations are the amounts of transport and construction energies used. These are likely to have the more significant effect on costs.
3. On-site cold recycling offers the greatest potential for energy conservation. However, the performance potential of the recycled pavement is an important consideration in considering the lifetime cost-effectiveness or lifetime energy-effectiveness. More information concerning the performmance of recycled mixes is needed for judging the lifetime effectiveness of different recycling options.
4. The cost and energy advantages for hot mix, central plant recycling depend greatly on the distances materials must be moved. As the distance the new aggregate must be hauled becomes increasingly greater than the distance between the asphalt plant and the job site, the advantages of recycling increase significantly. Conversely, as the distance between the job site and the asphalt plant become increasingly greater than the distance from the plant source of new aggregate, the cost and energy advantages of recycling reduce significantly. When asphalt plants are located at or very near the source of aggregate, and the job site is an appreciable distance from the plant recycling could require more energy and cost more than other alternatives.

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SPECIFICATIONS RELATED TO PROJECT SELECTION

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This paper discusses the work done by Mn/DOT in the last several years to develop specifications designed specifically for the maximum use of salvageable materials in the rehabilitation of pavements. It describes the steps leading to recent specifications for hot-mix recycling, the benefits derived, and the anticipated future of such projects. It also lists the problems involved with these specifications because of the general lack of historical information on projects involving recycling and/or rehabilitation. This report also presents information on Mn/DOT's sulfur extended asphalt projects including a sulfur extended asphalt-recycled project. The author recommends the changes that must be made before a specification is developed that allows competition between heater scarification, hot-mix recycling, and conventional hot-mixing. Other areas touched on are; removal, processing, storage and ownership of salvaged materials; different types of specifications; how to write new specifications; and the development of new specifications. The report contends that the design of a specification is so crucial that the very life of the concept (in this case, recycling and/or rehabilitation) may depend on it. One of the final conclusions is that the proper specification can lead to substantial savings. An example is offered where a savings of about 35% was experienced because a contractor was given the option of two specifications.

It is in the public interest for engineers, material suppliers and contractors to conserve resources such as aggregates and asphalt cement so that maximum use may be attained from the available supply. A large source of this supply has been processed and placed in our present pavement structures. Their usefulness as a pavement structure has deteriorated to the point that vehicle operating costs and pavement maintenance costs have increased so that the pavement is no longer efficiently serving it's intended purpose. Sound conservation practices demand that we design specifications to allow the maximum use of these salvageable materials to rehabilitate our pavements as long as their use is compatible with engineering and economic considerations. This paper will discuss some of the experiences in Minnesota to maximize the benefits of recycling salvageable materials. Most of our experience has been with hot-mix recycling. The design of recycling and rehabilitation specifications is crucial to whether or not the recycling of salvageable materials will be economical or even be accomplished at all. Our experience has shown that good specifications result when the interests of the user agency and the contracting industry are integrated and harmonized to produce maximum benefits.

Experience with Hot-Mix Recycling

Maplewood-Urban
1976 20,000 Tons 50-50;40-60 Blends Batch Plant

Minnesota's first hot-mix recycling project was constructed in Maplewood, Minnesota, in 1976. (1, 2, 3) This is the project that gave birth to the heat transfer concept of hot mix recycling. The existing aggregate base and asphalt pavement were processed into recycled base and binder courses. The major specification modifications were to process the salvaged asphalt material to a size smaller than 1½ inches, a provision that the salvaged asphalt mixture would not have to go through the dryer, and the temperature of the clean aggregate in the dryer could exceed the standard specification maximum. We learned that with the addition of 120-150 penetration virgin asphalt cement the penetration of the recovered asphalt cement from the recycled mixtures (new and old) was approximately equal to the penetration obtained by the thin film oven test of the virgin asphalt cement. We also found, in this case, that it was not cost effective to haul salvaged aggregate base material long distances back to the hot-mix plant site due to the low cost of new aggregate material. We were extremely pleased at the minimal cost for modification, the quality of the recycled mixture and the ease of laydown and compaction operations.

Fergus Falls-Rural
1977 50,000 Tons 50-50;60-40 Blends Drum

The following year, 1977, we reconstructed asphalt shoulders on Interstate 094 near Fergus Falls. (2, 4, 5) This was our first rural project and our first dryer drum recycling project accomplished using the heat transfer concept. The salvaged asphalt material was fed into discharge end of the drum with a slat conveyor. We recycled a blend of salvaged asphalt and salvaged aggregate material from 50-50 to 60-40 without excessive opacity at an acceptable production rate of 300 tons per hour. Although we were able to recycle the salvageable materials in the dryer drum, a continous mix pug mill was placed between the drum discharge and the storage tower in case the drum concept did not work. As the penetration of the old asphalt shoulder was very low (avg. 20) we experimented with adding 200-300 penetration asphalt cement in lieu of the 120-150 penetration asphalt cement we normally use. Even then, we had lower penetration on the extracted asphalt of the recycled mixture than we had anticipated. We believe the lower penetration possibly was due to the recycled material passing through the continous mix pug mill. We were satisfied with the mixture quality and pleased that the heat transfer concept was successful in a dryer drum plant.

Litchfield
1978 100,000 Tons 60-40 Blend Drum

In 1978, we recycled the old bituminous pavement and shoulders on a large rural project between Litchfield, and Atwater, on T.H. 12 (2, 6). On this project we did not specify the size of salvaged asphalt materials entering the drum mix plant. We did specify that the recycled mixture must pass the 2" sieve or one half of the course thickness when deposited into the truck at the plant site. All salvaged asphalt material was processed by dozers running over the stockpile and the use of scalping screens. The contractor would not use this method again due to the cost involved. The recycled mixture was produced at a 60-40 blend of salvaged bituminous material to virgin aggregate at an average production rate of over 450 tons per hour. The salvaged asphalt material entered the drum at the midpoint (center feed). All existing aggregate base was left in place in the roadbed. Base, binder and shoulder wearing courses were constructed with salvaged asphalt material and new virgin aggregate.

Additional Projects 1978
200,000 Tons 60-40;50-50;25-75 Blends

The above project was only one of several hot-mix recycling projects in Minnesota in 1978. We were encouraged by the variety of these projects, two state projects, two city projects, and two airport projects. We thought we were on our way with recycling in Minnesota. What we didn't realize was the amount of effort we were spending lining up specific projects for recycling. We also were unaware that recycling would fall off considerably in 1979.

Projects 1979

1979 was a disappointment for hot-mix recycling in Minnesota. We had very limited tonnage. We were using a permissable specification for recycling on several projects, however, no contractors were producing recycled mixtures on these projects. Because of this, we modified our specifications to pay for the old asphalt in the recycled mixture.

Projects 1980
30-70;40-60;50-50;60-40;70-30 Blends

This year, 1980, Specification 2332 (7) permissable hot-mix recycling produced recycled mix on several projects. We have a large airport runway project, an interstate project, and two trunk highway projects. We have turned the corner in hot mix recycling. Every contractor has the incentive to look at every project and weigh the costs and benefits of recycling vs. conventional mixtures. This specification is a part of all MnDOT projects. (8) No longer do we have to specify hot-mix recycling for specific projects. The contractor decides when and how to recycle and bids accordingly. We recently let a project which included the revised permissable hot-mix recycling specification. The contractors bid for the recycled hot mix portion of the project including mobilization was $547,163.03 compared to the engineers estimate based on conventional construction, of $837,970.85 for the same items. This represents a savings of approximately 35%. The first two bidders bid $65.00 and $66.00 per ton for asphalt cement compared to the engineer's estimate of $163.50/ton. The free market mechanism is working in Minnesota.

Experience with Heater Scarification

We have had limited experience with hot surface recycling in Minnesota. In 1978, we evaluated a project in Fridley. This method used heater scarification, then application of a rejuvenator. A hot mix wearing course was placed on the scarified layer several days later. In 1979, due to a shortage of funds, the state let a maintenance contract to provide a short term solution for a four lane expressway scheduled for reconstruction. This heater scarification procedure used a lead heater scarifier unit followed by a heater scarifier paver combination. Both units had the ability to heater scarify and add emulsified asphalt or rejuvenator. A hot-mix wearing course mixture was placed over the hot heater scarified pavement surface by the trailing unit. Earlier this year (1980) we used heater scarification on a portion of an experimental project using the same method as in Fridley, on a heavily travelled portion of Interstate 094 northwest of St. Cloud. The heater scarifier process was included as part of three 1-mile test sections which were developed to find an economical solution to our thermal cracking problem in the 1½" wearing course and the 2" binder course. The two other sections called for removal of the wearing course and both the wearing and binder courses with subsequent placement of new material. We have made several observations to date. At least on the more heavily travelled pavements, the heater scarification train using a trailing unit to place the hot mix wear course over the hot scarified material shows better pavement performance.

We would like to prepare alternative designs and specifications to allow competition between heater scarification, hot mix recycling, and conventional hot-mix. However, before we can accomplish this we feel some changes in the heater scarification specifications are necessary:

1. We have been unable to find any reference to density or void requirements for the old heater scarified material. We believe this should be required.
2. We also have experienced segregation of the heater scarified material.
3. Another problem is the addition of emulsified asphalt or rejuvenators to the scarified mat. The first problem that comes to mind is the water you are adding to the heated mat. This has to have a cooling affect and we don't believe water has any place in an asphalt pavement.
4. Another question? How do we insure uniform mixing of soft asphalt cement or rejuvenators with the hot scarified mixture.
5. We feel that in Minnesota a 3/4" depth of scarification of the old mat is the practical limit.
6. Many user agencies feel that heater scari-

fication procedures acts as a stress relieving interlayer to reduce reflective cracking. In the past we have not had any success with stress relief interlayers of any type. This does not include recent installations not yet evaluated.

It appears that the train method with the trailing unit (with integral paver) placing a new hot mix wearing course could be modified to produce a pavement structure that would be equal to recycled or conventional hot-mix if we would:

1. Require density and voids similar to those of hot-mix.
2. Insure a uniformly graded mixture without segregation.
3. Insure distribution of soft asphalt cement or rejuvenator in the scarified mat.

With these modifications we could take care of the rideability problem and produce a durable wearing course similar to a hot-mix overlay. This could also eliminate hauling of material to and from the hot mix plant.

Heater scarification could be an alternate to levelling and overlay if the pavement is structurally adequate and used with an overlay.

Experience with Sulphur Extended Asphalt and Sulphur Extended Asphalt-Recycled

1979 was a year we forgot about hot mix recycling. We experimented with two sulphur extended asphalt projects (9). One was a rural project incorporating approximately 44% sulphur to 56% asphalt cement by weight as binder. Gulf Canada provided the blending equipment and expertise. We were pleased with the results. The other project was a sulphur extended asphalt recycled, with salvaged asphalt material as a component as the paving mixture along with sulphur and new asphalt cement. Sulphur Development Institute of Canada provided the blending equipment and expertise. This project assured us that we could combine sulphur with recycled salvaged asphalt material without any problems.

Salvaged Materials

Source of Salvaged Material for Reuse

Where does the material come from to produce recycled pavements? Unless a contractor owns an aggregate supply or some other structure containing reclaimable materials, his source of reclaimed material must be provided by private industry or public agencies. A point to keep in mind is that it is not important where materials are obtained for producing paving mixtures. The quality and gradation of these materials is important as this will determine how they will perform in the pavement structure. Urban projects will differ from rural projects (10). Most of these materials will be derived from existing pavement structures. On large rural projects, the characteristics of these materials can be determined prior to design and construction and will in most cases, be salvaged and recycled into the new pavement structure. On urban projects, due to their relatively small size, the materials removed from the project can not easily be recycled and returned to the same project. Therefore, on urban projects, the quality of the material will be determined from the previously stockpiled material from many and varied sources. However, keep in mind that the characteristics of the materials incorporated into the paving mixture are the important aspects to be concerned about.

Removal of Salvageable Pavement Materials

Asphalt Pavement structures can be removed by ripping, scarifying and then processed for re-use. This is only practical when removing the entire structure. Prior to incorporating this material into a recycled mixture, crushing or processing to a smaller size will be necessary. This can be accomplished with conventional aggregate crushing equipment. The most popular seems to be a jaw with two rolls. The first roll will produce pancakes with the second roll breaking up the pancakes into small fragments. A cone crusher will require the addition of grouser bars on the cone to break up the pancakes into small fragments. Hammermills can be used on recycling projects that require ripping and scarifying. Hammermills most likely will be used for full depth inplace recycling.

Planing, either hot or cold, is capable of removing asphalt pavements to a specified grade or can remove the entire structure. This virtually eliminates the need for a crusher in the recycling operation. Up to 15% oversized material (over 2") can easily be crushed with a dozer at the plant site. It is also possible depending on the expertise and method of recycling to utilize fragments larger than 2" nominal size if the final mixture meets specifications.

Storage and Ownership of Salvaged Material

The entity responsible for producing the recycled mixture should be responsible for the removal, processing and recycling of these materials. For example, some user agencies have specified removal and stockpiling of asphalt pavement structure as a part of a separate grading contract. One of the basic problems in doing this is the lack of interest in retaining the inherent quality of the pavement removed and stockpiled. Experience has shown that deleterious and objectionable material have contaminated the stockpile thereby insuring an inferior recycled mixture with a large potential for premature failure of the recycled pavement structure. It also has allowed time for moisture contents to build up in the stockpile thus requiring fuel for drying, making pollution control more difficult, and reducing the rate of plant production of recycled mixtures. This adds unnecessary expense to the user. A simple way to eliminate this unnecessary expense is to make the removal, processing and stockpiling of salvaged material the responsibility of the persons producing the recycled mixture. Contractors who have this responsibility have the incentive to carefully remove process and stockpile these materials and keep costs to a minimum. This year contractors in Minnesota cover or construct their salvaged asphalt material stockpiles to prevent or reduce moisture buildup. With the price of liquid fuel near $1.00/gallon each 5% of moisture per ton of mixture will require $1.00 per ton to remove the moisture. Many unprotected stockpiles have moisture contents ranging from 5-15%. The user agency should not retain the ownership of salvaged materials unless they are willing to protect its quality. Ownership should go to the person controlling the end use of the material.

The user agency should pay for the removal of materials on a project. These materials will then become the property of the contractor to dispose of as he sees fit. This is what we have been doing with materials removed from all our projects in the past. The only difference was that most of these materials were being hauled to a landfill for disposal or disposed of within the right of way and not used in the pavement structure.

The user agency should allow the contractor to incorporate these potentially valuable materials into recycled mixtures for payment equal to conventional mixtures. In other words, these salvaged materials would continue to be hauled to landfills unless we were willing to use and pay for the recycled mixtures that could be produced from these materials.

By allowing the use and payment for salvageable materials in lieu of conventional materials, the user has established value for salvageable material. Unless this is done, salvageable materials will either be hauled to a landfill or as some enterprising contractors are doing, they will be incorporated into recycled asphalt mixtures for the private market sector.

Development of Permissable Hot-Mix Recycling Specifications

The first step in developing specifications for recycling were the special provisions used for the Maplewood project. We used the maximum size requirements from other recycling projects in Texas and Nevada. We designated the thickness of aggregate base to be salvaged. The gradation of the salvaged aggregate was required to be reasonably uniform from fine to coarse with 100% passing the 1½" sieve. The gradation of the processed salvaged bituminous material was required to have as reasonably uniform gradation from fine to coarse with 100% of the material passing the 1½" sieve.

The salvaged materials were measured and paid for by the ton. They were to be placed in separate stockpiles. We also allowed up to 20% salvaged aggregate to be incorporated into the salvaged bituminous to facilitate crushing or processing.

The standard plant mixed bituminous pavement specifications were modified as follows:

1. The contractor was required to submit an acceptable proposal for preventing or eliminating excess air pollutants.
2. A means for adding the salvaged bituminous material to the heated aggregate after the aggregate has left the dryer. Also positive control on proportioning the salvaged material into the mixture.
3. When adding salvaged bituminous mixture for the bituminous base and binder courses it may not be necessary to run the salvaged bituminous material through the dryer.
4. We gave the approximate mixture proportions which ranged from 20-40%, for salvaged bituminous and 60-80% for the salvaged aggregate.
5. Aggregate leaving the dryer could be heated in excess of 325 degrees F.
6. Costs for equipment modification at a lump sum bid not to exceed $15,000. Also required was the itemized cost for modification.
7. Payment similar to conventional mixtures except there was no payment for old asphalt cement in the salvaged bituminous material.

Our first change to the above special provisions occurred in 1978 when we deleted the 1½" maximum size in the salvaged bituminous material. The maximum size requirement applied to the recycled mixture after being processed through the hot mix plant and deposited into the transport vehicle.

Up to this point in time almost all our projects had been specifically designed for recycling. If recycling was ever going to reach its potential, we had to provide a permissable specification for allowing recycled mixtures in lieu of conventional mixtures on all projects. We also were spending to much engineering time setting up projects for recycling without really knowing for sure, in some cases, whether recycling was cost effective.

Therefore, in 1978, we began the development of a permissable hot mix recycling specification to allow the contractor to use recycled mix in lieu of conventional mix. As a part of this specification, we made several significant changes. The most important change was to establish mix design criteria from recycled mixtures. They are as follows:

Using the representative samples submitted and the proposed proportion of each, trial mix tests will be run to determine the percentage of asphalt, by weight to be added. The following criteria will be used to determine the percentage of added asphalt required:

1. *Marshall Stability (50 below)
   - Minimum...................... 500 lbs.
   - Maximum......................3,000 lbs.
2. *Voids in Mix
   - Minimum...................... 4%
   - Maximum...................... 6%
3. *Cold Water Abrasion Loss
   - Non Wearing.................. 15% Max.
   - Wearing...................... 10% Max.
4. In no case shall the percentage of salvaged asphaltic concrete in the recycled mixture exceed 70 percent by weight.

* Test procedures on file in the Department of Transportation's Materials Engineering Laboratory at the Transportation Building in St. Paul.

No recycled mixture shall be produced for use on the project until the amount of asphalt material to be added with the appropriate blend has been established.

After the percentage of added asphalt has been determined, it and the proportions of the other materials used in making that determination shall remain in effect until modified in writing.

Another change was establishing a job-mix formula if virgin aggregate was used in recycled wearing course mixtures. The requirements are the same as those required for conventional wearing course mixture. The job-mix formula applies only to the virgin aggregate portion of the recycled wearing course mixtures. The virgin aggregate portions of recycled base and binder courses must meet the broad gradation bands similar to conventional base and binder course mixtures. We do not do design mixes for conventional base and binder mixtures.

This specification was included in many projects to be let in 1979. However, contractors were not using the specification, therefore, the volume hot-mix recycling did not meet our growth expectations. It did not take long to realize that the way our pay items are set up in Minnesota, if we were to continue not paying for the old asphalt cement in our recycled mixtures there would be little, if any, recycling.

This led to our most important and controversial change in our specifications, paying for the old asphalt in the salvaged bituminous material. Several engineers in Mn/DOT did not agree with the philosophy of paying for asphalt cement we already owned. However, the free market mechanism compensates for this in the competition bidding process.

An explanation of why it is necessary to pay for old asphalt cement is best accomplished by the following. The first step before a contractor can build a project is to be the lowest successful bidder. Our permissable recycling specification allowed recycled mixtures in lieu of conventional mixtures. However, if the contractor was the successful bidder and decided to recycle he would get payment only for the new asphalt cement added to the recycled mixture. For example, if the project called for 20,000 tons of asphalt mixture at a bid price of $10.00 per ton and 1000 tons of asphalt at a bid price of $100.00 per ton, the contractor would be paid $300,000 for the constructed pavement. Remember, first of all, he had to bid low to get the job. Then, if he decided to recycle he would get the bid price for the asphalt mixture and if he saved 500 tons of asphalt cement by recycling he would be paid a total of $250,000 which produces a loss of $50,000.

You can see the contractor had no incentive to recycle. So we had to find a way to compensate the contractor for the value of the asphalt cement in the mixture. The method chosen was the Colorado Extraction method applied to the final recycled mixture. Under the revised specifications the contractor is paid for the amount of virgin asphalt added to the mixture plus the amount of old asphalt in the mixture.

This has been the key to establishing hot-mix recycling in Minnesota as a standard operating procedure. In 1979, we had one supplemental agreement where a contractor used the new specifications. This year, 1980, the permissable specifications are being used on all projects. (7)

Selection of Alternative Recycling and Rehabilitation Procedures

When writing specifications for recycling and rehabilitation procedures, keep in mind who is best able to make the decisions that will maximize the benefits of recycling and rehabilitation procedures. The designer and the staff specialists such as the bituminous engineer, materials engineers, research engineers, planner, etc., have a very important role to play in determining the present condition of the pavement and what the pavement will be expected to provide in the future. A very important factor today is the lack of funds to most cost effectively provide an acceptable transportation system. Funding levels will have a heavy impact on the best available solutions which will provide the most appropriate level of service to the public. Another problem facing us is the lack of a defensible service life of various rehabilitation procedures. In absence of long term evaluation for durability a best estimate of service life must be determined. This is best accomplished by a team of experts. From this best estimate future modification to the estimate will be forthcoming as time and testing provide more precise answers to service life. We are beginning the process of establishing service lives for recycling and rehabilitation procedures in Minnesota. The Federal Highway Administration is also establishing a data bank on recycling projects. This should help guide us in the future.

Method Vs. End Result Specifications

There are basically two types of specifications. Method specifications, which specify exactly how to do the work, what equipment to use, how to use it, and to some extent, what the end result should be. End result specification leaves it up the contractor to provide the end result without instructing him how to produce that end result.

The most practical specification is a combination of method and end result specifications that combines the expertise of the user agency, contractors, material suppliers and equipment manufacturers to produce a good end product almost all of the time at a reasonable cost.

Energy

The engineer need not concern himself with the energy saved or consumed for any design alternative provided the cost of energy is reflected by free market condition and so long as the specifications permit realistic alternatives to the bidders.

Development of Specifications

As you can see, the thrust in Minnesota is to develop permissable recycling specifications along with alternative rehabilitation procedures which will allow the contractors as much latitude as possible. However, this cannot be accomplished unless we find a way to make recycling a standard operating procedure. Each user agency must develop their own standard specifications for hot, cold and surface recycling. In most cases, the state user agency should be the leader in establishing these specifications.

The question then becomes, how do we transition from our past practice of almost exclusively building pavements out of new materials to one of utilizing salvaged or reclaimed materials for reconstructing or maintaining our pavements. This is a new and challenging field. More challenging than new design and construction because we have to find new ways of evaluating recycling methods and materials and predicting their future performance. If you thought performance of our old designs were difficult to determine, recycling procedures are infinitely more difficult to predict. However, we have no choice. We have to make intelligent decisions based on past experiences until more definite data is available for modifying our initial performance predictions. The initial answer will be to look at the properties of these salvaged materials in comparison to the materials used in the past. This is what we have done with hot-mix recycling. This is what we are doing with sulfur-extended asphalt mixtures. (11). As with any new product or procedure, we measure its properties and performance in relation to what we have done in the past.

We cannot wait another 15-20 years to determine the actual service lives of recycling and rehabilitation procedure. By waiting, millions of tons of potentially reclaimable material will be wasted and forever lost at a tremendous cost to the public. Also keep in mind that recycled pavements can have an added bonus of costing less than our conventional pavements. Another important benefit is less demand for new aggregates and asphalt cement, both non-renewable resources. Another important benefit is that landfills in our urban areas will take longer to fill and reduce the demand for new landfill sites further and further from the source of waste material thus reducing the cost of transportation.

Each area of the country must start with the specifications they are now using and begin to modify them by comparison with the practices a number of experienced agencies as expressed in their specifications. There are many specifications to study and evaluate when writing your own specifications. Your specialists responsible for writing your specifications know your area of the country and are best equipped to modify or create specifications that will fit your area. In addition, you should involve the contracting industry to assist and help you write specifications that will allow the free market mechanism to work. There should be as many alternatives as possible to allow maximum competition which will produce the desired product at the least cost.

In summary, the user agency should:

1. Be responsible for the adequacy of design alternatives.
2. Write simple straight forward specifications which clearly state what is expected.
3. Permit the contractor to select the materials and methods which will accomplish the end result.
4. Use standard specifications familiar to the contractors.
5. Modify standard specifications only as necessary to obtain the end result.
6. Focus on end results by allowing the contractor flexibility in choosing the most economical methods and procedures to accomplish the work.

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QUALITY CONTROL OF RECYCLED ASPHALT CONCRETE MIXTURES

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This report addresses the numerous considerations a contractor must give to material quality and process quality control as they relate to the recycling of asphalt pavement. Suggested quality control procedures are described, beginning with the pre-bid evaluation of the asphalt pavement being considered for recycling. Also described are the quality parameters that influence this evaluation. Removal methods and the stockpiling techniques employed are discussed as well as the process control which occurs when the recycling is done. Differences between actual and anticipated field conditions are mentioned throughout the report. Considerable emphasis is placed on the inadequacy of the present standard testing methods and procedures when used for process control of recycled asphalt. The serious shortage of qualified technicians needed to fill the positions recycling has created for them is also discussed.

Gallagher Asphalt Corporation has been in the asphalt recycling business since April, 1977 with the first pile of salvaged mix, or as it's called now RAP. That means Reclaimed Asphalt Pavement. All the reasons for being in this business will be apparent after listening to three days of recycling talks.

Unfortunately, today too many people are too contented with the status quo. Far too many federal, state, county, city, and consulting engineers are contented with the way things have "always" been. Far, far too many brother and sister contractors fall into this category too. It's truly amazing how much foot dragging goes on in this business, but that's human nature. When the funds go flat, and the resources go flat, and the competition for work gets vicious, there'll be a great deal more interest in this "new idea" from both sides of the marketplace.

Today the most beneficial thing to do is provide, or highlight, the challenges, and the opportunities that face the pioneers in this hot recycling game with emphasis on quality control in project selection. The following statements are practical and realistic insofar as hot mix recycling is concerned.

1. There must be a true economic benefit to both buyer and seller.
2. There must not be any significant reduction in performance in the finished pavement.
3. There must be a means and a method to control the finished product that will provide quality assurance to the buyer and product confidence to the seller.

Of these three points, economics and performance will be thoroughly treated at this Seminar. Quality control probably will not get the emphasis it deserves because today it offers many more problems than it does solutions.

There is much to be done by industry and technologists in the area of quality control of recycled mix. The approach in this paper will be to look at things as they are for Gallagher Asphalt today, and also as they will become when recycling finally is a fully accepted practice and is generally permitted for all types of bituminous work. This is in contrast to the way most recycling has been done to date--a few large, carefully selected jobs involving both the removal of old pavement and its re-use on a specified project.

Most of the recycling in the future will be done as a contractor option on all types of work and the salvaged asphalt used will not have been earmarked for such use in advance. It will come from accumulated piles of RAP hauled in from prior asphalt removal jobs and stored in the contractor's yard for later use on some, as yet unknown, job. Much of the quality control, or rather quality assessment, is done (or should be done) long before there is an actual recycling.

Assessments of the Existing Pavement Quality

As stated in the beginning, there must be an economic benefit to both buyer and seller and an economic evaluation is always the first thing to be done. Along with, and a vital part of the economic assessment, is a quality evaluation. The old adage "you can't make a silk purse out of a sow's ear" still applies. The potential, ultimate use of salvaged pavement must be decided before doing anything. Once this is determined, then economic criteria can be applied and a rational decision made to recycle or waste the reclaimed pavement.

How is this done? There is just one way--sample and test, sample and test. That's the name of the game. Contractors rarely do a thorough job of this and the reason most of the materials that have been salvaged to date for the most part were originally built under modern specifications, using the same raw materials used today. This is true in Gallagher Asphalt's case as their asphalt plants have been in Thornton for over 50 years. For many people this won't be the case. Then a more or less extensive sampling and testing program needs to be carried out.

It's worthy of mention here that sometimes the method of removal of the old pavement could make or break the possibility for future recycling. If the upper levels of the roadway are composed of high quality materials and the lower strata is inferior, for whatever reason, recycling potentials can't be evaluated without also deciding on the removal method.

It is of prime importance that this be considered by all those concerned with the project. At times an excavator ends up as low bidder on a pavement removal project and naturally figures the cheapest way to remove the pavement, never considering the potential of re-use or re-sale of the RAP to an asphalt producer. Valuable material can be lost forever because it was contaminated in the removal process.

Perhaps a simple note in the bid proposal stating that a certain portion of the "to be removed" pavement has recycling potential would be all that is needed. This should alert the bidders to a potential cost benefit when figuring the work. It is not advocated as a bidding requirement that pavement be removed in a certain manner so that it can be recycled. Free market competition should prevail so that the taxpayer gets the best buy all around, with or without recycling. However, it might be a good reminder for a while to mention this potential in the bidding documents, since it is such a new concept to most people.

Assuming the contractor doesn't have any knowledge of how good or how bad pavement to be removed is, he must go out and sample it. This presents at least two problems.

1. The owner probably didn't allow enough lead time for the contractor to do much or any testing prior to bidding, and
2. The owner doesn't really want hordes of contractors punching holes all over the project before it's even let.

The only solution is for the owner to determine the quality of existing pavement and publish these data in the bid documents. Again, there are trade-offs to consider. Is the potential decrease in the bid price worth the cost to do the testing prior to issuing proposals? Each authority must make this judgment on the pavement removal projects under their jurisdiction.

Handling the Reclaimed Asphalt Pavement

Assuming the pre-bid testing has been done and the recycler has made a judgment in favor of retaining the salvaged material for future recycling, the second stage of quality control begins. If the material is removed in layers by means of planers, and some degree of job control is exercised to keep the surface material separate from the binder, etc., there is a good chance for some real high quality material that can be recycled at a high ratio in a surface mix. If, however, the job control and/or stockpiling techniques are poor, there could result a stockpile combination that is only good for base work due to the blending of gradations. It's important that everyone be fully aware of the intended uses of this salvaged material so that it is handled by the contractor's own forces as a raw material with real value.

For a lot of years, job foremen have sent this material to refuse dumps for disposal, and it's going to be some time before they are re-trained to realize that this is a valuable commodity whose quality must be maintained. To illustrate, there are continual problems with field people disposing of old planer teeth, lunch bags, beer and pop cans, two-by-fours, concrete curb, broken sewer castings, etc., etc., in the would-be reclaimed material.

When running a recycled mix through a batch plant, a broken sewer casting can sure shatter all dreams of profit when it hits the pugmill. In more extreme cases, state forces cleaning up the shoulders, ditches, and catch basins ahead of the milling or planing operations have deposited this trash in front of the planer to save time. Even the situation where the street sweeper subcontractor dumps the sweeper in front of the milling machine to save trip time to the dump has occurred.

Once the material is loaded and brought to the plant site, there is the potential for a lot of triage. It must then be decided what gets dumped where. This is a problem now, but in the future it's going to get a lot worse. If it's known what is in those truckloads of salvage mix, that's a big edge on the problem. If the material quality is unknown at this time, it can be a serious problem. Generally speaking, the contractor should try to keep piles separated by mix type--base, binder, and surface but also have a GOK pile. Translated, that means God Only Knows.

It's fortunate to have predictable sources of RAP so that gradation, asphalt content, and aggregate quality are quite consistent for each type of mixture stockpiled. Twice blessed are those who have a good bit of stockpile space at the plant, and can afford the luxury of numerous, separate piles. Contractors not situated to handle this inventory problem are at a disadvantage to stockpile RAP and speculate on future uses for it.

It isn't necessary to do a great deal of testing prior to stockpiling if the quality and uniformity of the RAP are pretty well known before it's ever tested. Most contractors simply don't have enough skilled manpower to perform much testing; and the testing, to be very helpful, would need to yield fast answers so that decisions as to where the material should be piled could be made promptly. No existing test procedures are that "quick".

Recycled Mix Quality Control

Asphalt Content

This leads to the next problem level of quality control--how to maintain on-going mix quality control? Given a shortage of capable technicians, time, and testing methods, it is very difficult. Any experience with any of the popular extraction testing techniques will show that none of them are very fast and all are of questionable accuracy and reproducibility, especially when using different technicians and test methods. On top of this is the fact that extractions of RAP require considerably more time to complete than does a conventional mix extraction--moisture, hard asphalt and generally higher 200 mesh material add hours to the time needed to complete these tests. Under preset methods one can expect to get two RAP extractions maximum a day--usually only one per technician. The present state-of-the-art in mix extractions is the major impediment in good quality control of RAP.

To illustrate this with some figures, an Illinois DOT materials man using the Colorado vacuum extraction--the fastest method available--takes 3 to 3½ hours to wash the reclaimed aggregate sample clean and uses 2 to 3 times as much solvent as normally would be used on a virgin mix extraction test. It takes from 2½ to 3½ hours just to dry the sample to a constant weight. The Illinois DOT central lab tried it in a reflux extractor and it took 2 days to complete one test. This is not an acceptable length of time for RAP testing.

The asphalt industry deperately needs a better and faster method of determining the asphalt content and gradation of mixtures. The three popular extraction methods--reflux, centrifuge, and Colorado vacuum--are not good enough today. These methods require too much "operator technique" and too much time. This is not only true of RAP, but also the regular or conventional virgin mixtures. Someone out there must come up with a better mousetrap.

Generally stockpiling RAP occurs before it's known where, when, or even if it will be used, so it's usually stockpiled on the South 40. When a job comes along and the RAP material that can be used in conjunction with virgin aggregates and asphalt to turn out an acceptable mix is available in the back lot, this stockpiled material is moved into a "working pile" close to the plant. This pile must be tested once or twice each day and, if necessary, the mix adjusted. Gallagher Asphalt uses a running average of the last three extractions as a "representative sample" (see Table 1). The State of Illinois DOT uses a running average of 10 extractions. Perhaps 10 are too many and 3 are not enough--this will, in time, be fine tuned and will probably end up with five extraction samples as being most "representative". Again it should be noted that faster testing would dramatically improve control.

RAP Percentage

One final way, and the best way today, to hedge uncertainty is to limit the percentage of reclaimed material used in the recycled mix. Illinois DOT permits a 50/50 proportion in batch plants, but at such a ratio temperature, gradation, and asphalt control become critical. To limit risk, it is a good idea to recycle at lower RAP percentates. Gallagher Asphalt typically recycles at 30% RAP, but frequently will use as little as 10%.

For the time being, the available supplies of RAP will be used up even at low recycle ratios, and by maintaining lower percentages there is a lot better chance of turning out a high quality product. The cost savings on a fixed available quantity are the same no matter how fast it's used, so the contractor should be conservative and recycle at low ratios. This does not mean to say that one must recycle at this low a percentage--it just seems more prudent to do so at this point in time. As RAP becomes more available, higher recycling ratios will be necessary in order to utilize the maximum benefits of the "new" material.

Gallagher Asphalt Test Program

The method of quality control used by Gallagher Asphalt is as described, that is to say, on pavement removal jobs where the company has been involved in the original construction and/or has gathered information concerning the material and mixture used in the original construction, assumptions are made as to the mixture grading and A/C content. If such information is not available, samples are taken on a random basis from the roadway, usually at 500 ± foot intervals per lane. At least 10 samples per job are obtained. Based on extractions of these material samples the potential value of the RAP for recycling is evaluated.

Once the job has been awarded and removal has started, the plant dump location is selected based on what the initial assumptions and/or sample reports showed concerning gradation--if it's typical of binder that is in the stockpile now, the material is added to that pile; if it's surface, the same is true; and finally if it's base, it is added to the base pile. Generally speaking, if it's a conglomeration of binder and surface, or base, binder and surface, or just base, these materials are all mixed together in the base pile. These materials are then used only for base construction.

When the time arrives to use the material, it is moved from the stockpile area into the working pile. This is a relatively small pile of material located close to the plant. The in-process quality control routine then begins. This routine involves daily samples (usually one or two) of the working pile. Based on the average of the last three samples extracted from this working pile, adjustment is made of the gradation and/or asphalt content of the mixture.

So far this routine has worked satisfactorily, however, if reclaimed aggregate percentages greater than 30% were used, one would question the reliability of the meager extraction data gathered for this purpose. Naturally once the RAP material is combined with the virgin materials in the asphalt plant, on-going extractions of the completed mixture are conducted which are compared with the preliminary calculated mix proportions.

The Future of Recycling

So what's ahead and where is change needed? The industry is just beginning to grasp the potentials of recycling pavements. In the not too distant future, recycling will go on all the time on all types of work. The road planer or roto-mill has just begun to reshape thinking about roadway rehabilitation and maintenance. At this time, structural pavements made from recycled old pavements and surfaced with skid resistant wearing courses which themselves will be reclaimed and re-used as they become ineffective or "worn out" seems a reasonable projection.

There is economic pressure for more and more use or re-use of materials such as the many types of slags, glass, fly ash, kiln dust, incinerator residue, etc. Though it's nice

Table 1. Percent A/C Contributed by RAP - Recycle (RAP) for Kingery BAM & Binder RAP

Tested By	Date 1980	Today's A/C Content of RAP	Avg. of Last 3	Residual A/C Contributed by RAP % RAM Added to Mixture 15	18	21	24	27	30
HLC	5/14	4.3							
HLC	5/15	4.9							
HLC	5/16	4.3	4.5	.7	.8	.9	1.1	1.2	1.4
GACO	5/16	4.9	4.7	.7	.8	1.0	1.1	1.3	1.4
HLC	5/17	4.4	4.5	.7	.8	.9	1.1	1.2	1.4
GACO	5/17	4.6	4.6	.7	.8	1.0	1.1	1.3	1.4
GACO	5/20	4.9	4.6	.7	.8	1.0	1.1	1.3	1.4
GACO	5/21	4.7	4.7	.7	.8	1.0	1.1	1.3	1.4
HLC	5/21	4.6	4.7	.7	.8	1.0	1.1	1.3	1.4
HLC	5/22	4.4	4.7	.7	.8	1.0	1.1	1.3	1.4
GACO	5/22	5.0	4.7	.7	.8	1.0	1.1	1.3	1.4
HLC	6/5	5.1	4.8	.7	.9	1.0	1.2	1.3	1.5
GACO	6/16	5.0	5.0	.6	.9	1.1	1.2	1.4	1.5
HLC	6/17	4.7	4.9	.7	.9	1.0	1.2	1.3	1.5
HLC	8/6	4.8	4.8	.7	.9	1.0	1.2	1.3	1.5
HLC	8/7	4.7	4.7	.8	.8	1.0	1.1	1.3	1.4

to think these things are being used for "patriotic" or some other high sounding reason, the truth is they're used because they have become economically feasible. Depletion and high energy costs have turned the tables on "the way we always done it". With this increased use of waste products and re-use of finished products, it is a totally new ball game.

Can industry, associated technical schools, colleges, and the school of hard knocks meet the demands of this new way of doing business? From the way things look right now, this industry just won't be tooled up in time. Most contractors are ill equipped to handle the varieties of materials and technology that will be needed to cope with these new problems. The availability of any skilled technician is horrible right now and tends to get worse rather than better as time goes on. The states and other public agencies are cutting their field and lab manpower at an ever increasing rate.

Consider this--back in the days when it was grounds for celebration when a plant produced 1,000 tons a day, there were several state people in the plant inspecting everything all the time. Now, when plants are capable of 6,000 tons per day on a routine basis, the state department of transportation has difficulty finding one plant inspector or proportioning engineer and he's so busy filling out forms he can't inspect anything anyway.

The only hope is to encourage the contractors to get into in-house quality control programs, convince the powers that be (that means politicians and bureaucrats) that the action that counts is in the field not in the piles of "documentation" they presently require, and immediately develop better and faster testing methods and equipment. Finally, and perhaps the most vital, encourage the trade schools, colleges, and universities to offer and promote more courses on quality control in this field of construction materials.

PROJECT SELECTION IN URBAN RECYCLING

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Pavement recycling problems in the urban environment are different than those in rural areas. The size and magnitude of the projects are generally smaller in scope. Also, there are many more physical constraints ie: curbs and gutters, catch basins, driveways, cross gutters, median curbs, manholes, etc., which influence the design. A typical economic analysis is presented as well as evaluation criteria. Presentations should be made to local officials, planners and citizens showing that the benefits of recycling far outweigh any inconveniences a few may encounter. Encourage local contractors to obtain the equipment needed for recycling by demonstrating that it is economical and beneficial. Also inform them of the agencies intention to utilize this construction technique.

Project Selection

Is this project a candidate for recycling? This question should be asked on all reconstruction, resurfacing and widening projects. The answer will probably be yes, even if the project is very small (1/10 to 1/4 mile). No longer can the economic and environmental potential through recycling be ignored, but these considerations must be evaluated on each project. If the economics are not favorable, the removed asphalt concrete can still be utilized on a future project by stockpiling it, thereby conserving our natural resources and fuel. Environmental and economical considerations may dictate whether hot, cold or surface recycling should be used.

With a trend towards the 3 R's--resurfacing, restoration and rehabilitation of our interstate highways, county roads and local streets, recycling of the existing worn and tired pavements is a very important development and technique. Recycling should be added to the highway engineer's arsenal for the maintenance and construction of the transportation system.

In the urban environment, most of the roads and streets are improved with curb and gutters, catch basins, cross gutters, driveways and in some cases raised median curbs, which control the geometric and horizontal alignment and many times also provide the vertical control for finished pavement elevation. With these types of controls, considerable problems can be encountered in designing and placing a thick asphalt concrete overlay. Some of the typical problems resulting from thick overlays are excessive crossfall ie: car doors cannot be completely opened (Figure 1), ridability of cross gutters (Figure 2) and driveway access (Figure 3), reduced water carrying capacity when storm runoff either tops the curb or extends further out into the traveled portion of the roadway than originally designed, loss of curb height of median barrier curbs (Figure 4) and raising of manholes or utility vaults (Figure 5). Recycling of the existing asphalt concrete roadway can reduce the magnitude or eliminate some of the problems illustrated.

Public Relations

When evaluating a project and determining if recycling should be used, project location often limits the techniques available when working in a central business district, industrial or residential area. Traffic control considerations which must be evaluated are: Will a detour be required, can construction proceed utilizing a portion of the existing roadway or can the street be closed during construction?

Being good neighbors is a must and will require determining the effect the increased dust and noise will have on the adjacent properties when selecting inplace vs. offsite recycling techniques. With the the equipment available today, inplace cold mix or surface recycling can be accomplished in most urban areas without adversely affecting the environment. The location of existing asphalt batch plants or material storage areas for the removed asphalt concrete must be included as part of the economic study when determining fuel, aggregate and paving asphalt cost savings through the use of recycled materials.

It is incumbent upon the engineer to inform their local officials and citizens about the value of reusing the existing pavement materials and that the economical and ecological benefits far outweigh any inconveniences a few may encounter. If necessary, be prepared to go before your local planning commission to request their cooperation in granting contractors permission to move in onsite crushing or mixing equipment, on a temporary basis, which may not meet the local zoning requirements. Stress that they are helping the local economy, the environmental and ecological balance by conservation of material resources and conserving energy when the asphalt concrete and untreated aggregate are recycled. Also point out that pollution is being reduced even though some additional localized noise and dust may be created.

Pavement Analysis

Should the project have only localized areas of distress, recycling can very effectively be used in the distressed areas and then an overlay or a surface treatment placed to complete the project. It has been demonstrated, when localized failures occur only in the surface portion of the structural section, that cold planing or milling out a portion of the asphalt concrete can make an economical repair with recycled asphalt concrete. In addition to the savings previously mentioned, a double benefit may be derived from trucks by having them haul the milled material to a plant or storage site and bring back asphalt concrete to the project site for placement in the milled area. This construction method has proven to be very effective in the business districts and industrial areas. Work can begin on the traffic lanes after the morning peak and have them completed and ready for use in time for the evening rush hour, thereby eliminating the need to barricade off a portion of the roadway or detouring traffic around the project. If the distress in the roadway is related to the untreated base material, then by recycling the asphalt concrete surface and the untreated base into an asphalt concrete material a significant structural improvement can be attained. Thus, the structural value and load carrying capacity of the pavement can be increased considerably with no increase in thickness or change in grade.

On the other hand, if a roadway is structurally adequate but has developed significant amounts of cracking due to aging, its integrity and ridability can be improved though recycling. It is also possible to reprofile a street with recycling. These generally can be accomplished through surface recycling techniques; however, cold or hot recycling can also be used if a considerable depth of asphalt concrete is to be removed.

Many projects which would be postponed awaiting funding or permitted to further deteriorate prior to reconstruction can be effectively rehabilitated at a lesser cost by using recycling.

Economic Analysis

A typical economical analysis for a small urban hot recycled asphalt concrete mix is presented in Table I. It should be noted that by recycling the existing asphalt concrete, significant savings can be accomplished, $2,000 - $2,800. These savings relate to lower project costs.

The relative locations of the aggregate sources, batch plants and dump sites to the the project location can greatly affect the savings. Both of these batch plants are about equidistant from the aggregate source. The Inglewood plant which is closer to the project site and further from the dump and refinery shows a greater savings when compared to the Gardena plant. However, the expected savings will probably be nearer the calculated maximum of $2,800 due to the competitiveness of the two plants. This competitiveness can only be accomplished after demonstrating to the contractors that whenever the economic and design considerations are favorable, recycling will be specified.

Surface recycling was not considered on this project because of the pavement condition (Figure 6) and inadequate existing structural section. Cold recycling the surface with the existing sand subgrade was considered but discarded because of underground utilities and grade controls due to drainage problems.

The use of recycling must be approached in the same manner that an overlay or new construction project is being evaluated. That is, the project must be planned, programmed and scheduled to take maximum advantage of available economics.

Do not just plan one or two projects and then wait 5-10 years after they are constructed to thoroughly evaluate their effectiveness. Take advantage of the work previously done by other agencies and contractors. Review their reports, talk to the design, construction and maintenance engineers as well as the contractors and learn firsthand what their experience has been and how they have improved and refined their construction and design procedures. Before a local contractor will invest in recycling equipment, he must be assured that recycling is economical and part of an ongoing highway program. Economic studies of projects (even previously constructed nonrecycled projects) can help indicate the number of projects you may have per construction season. Once a market for recycling is created and more contractors become equipped to do this work, the greater will be the competition and also the savings to the agency.

Remember, that recyling of the existing roadways, combined with your resourcefulness, ingenuity and determination, will provide an additional economical method to continue to improve and maintain your highway and street systems to the highest standard.

TABLE I

PROJECT EVALUATION

Project: Mariposa Street   Location: City of El Segundo

Limits: 565' W/O Nash to Douglas St.   Length: 1850 ft.

Existing Structural Section: 3" AC on Native Sand

Condition: Badly Alligatored

Existing Improvement: Curbs & 1' gutters @ 25' from C.L.

Proposed Improvement: Curbs & 2' gutters @ 32' from C.L. and 4" AC on 10" Aggregate base.

Area: 1850 ft. x 60 ft. = 111,000 S.F.

Asphalt Concrete required: 4" x 111,000 sf. x 145 pcf. ÷ 2000 = 2700 tons (94.7% Aggr., 5.3% Asphalt)

Surface Course 1000 tons, Base Course 1700 tons. Recycled Asphalt Concrete to be used in base course only.

Economic Analysis based on asphalt concrete batch plant located in Gardena

Distance:	Aggregate source to batch plant	30 miles
	Paving Asphalt source to batch plant	8 miles
	Batch plant to project site	9 miles
	Project site to dump site	8 miles

Costs to get materials to batch plant

All new aggregate asphalt concrete

Virgin Aggregate	2700 tons x 94.7% x 30 mi x $0.10/ton-mi	= $7,671
Paving Asphalt	2700 tons x 5.3% x 8 mi x $0.60/ton-mi	= $ 687
	Total	= $8,358

Recycled asphalt concrete (30% reclaimed aggregate + 70% virgin aggregate) to be used in base course of asphalt concrete only.

Base Course asphalt concrete

Reclaimed Aggregate	30% x 1700 tons x 94.7% x 9 mi x $0.30/ton-mi	= $1,304
Virgin Aggregate	70% x 1700 tons x 94.7% x 30 mi x $0.10/ton-mi	= 3,381
Paving Asphalt	70% x 1700 tons x 5.3% x 8 mi x $0.60/ton-mi	= 303
	Subtotal	= $4,988

Surface Course Asphalt Concrete

Virgin Aggregate	1000 tons x 94.7% x 30 mi x $0.10/ton-mi	= $2,841
Paving Asphalt	1000 tons x 5.3% x 8 mi x $0.60/ton-mi	= 254
	Subtotal	= $3,095
	Total	= $8,083

Haul costs & dump fees for removed existing asphalt concrete pavement.

Haul to dump (30% of 1700 tons)	510 tons x 8 mi x $0.30/ton-mi	= $1,224
Dump fee	510 tons x $1.00/ton	= $ 510
	Total	= $1,734

Savings using recycled aggregate =

Asphalt Concrete (new aggregate)		Haul & Dump Costs (exist pavement)		Asphalt Concrete (recycled aggr.)	
$8,358	+	$1,734	–	$8,083	= $2,009

Economic Analysis based on asphalt concrete batch plant located in Inglewood

Distance:	Paving asphalt source to batch plant	16 miles
	Aggregate source to batch plant	33 miles
	Batch plant to project site	4 miles
	Project site to dump site	8 miles

Costs to get materials to batch plant

All new aggregate asphalt concrete

Virgin Aggregate	2700 tons x 94.7% x 33 mi x $0.10/ton-mi	= $8,438
Paving Asphalt	2700 tons x 5.3% x 16 mi x $0.30/ton-mi	= 687
	Total	= $9,125

Recycled asphalt concrete (30% reclaimed aggregate + 70% virgin aggregate) to be used in base course of asphalt concrete only.

Base Course asphalt concrete

Reclaimed Aggregate	30% x 1700 tons x 94.7% x 4 mi x $0.30/ton-mi	= $ 580
Virgin Aggregate	70% x 1700 tons x 94.7% x 33 mi x $0.10/ton-mi	= 3,719
Paving Asphalt	70% x 1700 tons x 5.3% x 16 mi x $0.30/ton-mi	= 303
	Subtotal = $4,602	

Surface Course Asphalt Concrete

Virgin Aggregate	1000 tons x 94.7% x 33 mi x $0.10/ton-mi	= $3,125
Paving Asphalt	1000 tons x 5.3% x 16 mi x $0.30/ton-mi	= 254
	Subtotal = $3,379	
	Total	= $7,981

Haul costs & dump fees for removed existing asphalt concrete pavement

Haul to dump (30% of 1700 tons)	510 tons x 8 mi x $0.30/ton mi	= $1,224
Dump fee	510 tons x $1.00/ton	= 510
	Total	= $1,734

Savings using recycled aggregate =

Asphalt Concrete (new aggregate)	+	Haul & Dump Costs (exist pavement)	-	Asphalt Concrete (recycled aggr.)	
$9,125	+	$1,734	-	$7,981	= $2,878

Figure 1.

Figure 2.

Figure 3.

Figure 4.

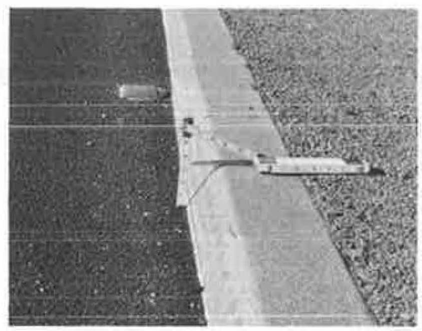
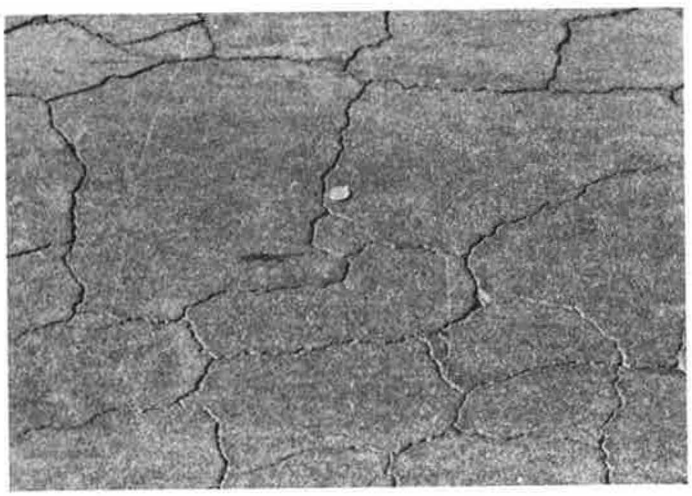


Figure 5.

Figure 6.



PROJECT SELECTION FOR RURAL RECYCLING

Bobby R. Lindley, Assistant District Engineer, State Department of Highways and Public Transportation, Abilene, Texas

Definition of recycle literally and in terms of highway construction. Identifying size, magnitude, and miles of highway considered in the Abilene District of the Department of Highways and Public Transportation. Laboratory and design techniques used to arrive at a design for the proposed construction. This includes District policy and other relative items. Examples of several types of rural recycling used in rehabilitation projects. Summary statements.

The subject being discussed here today indicates to me that we are only looking at rehabilitation-type projects. Webster's Dictionary defines recycle: "to pass again through a series of changes or treatments: as, to process in order to regain material for human use, to return to an original condition so that operation can begin again".

The above definition does not indicate a specific place or time schedule for the use of a recycled material. The boundaries for recycling existing streets and highways are not, and have not been, defined and I submit that no such boundaries should be placed on this relatively new concept in roadway construction.

The title of my presentation is Project Selection for Rural Recycling. In order to follow the program discipline outlined for us, I will try to give you the method we use in District 8 of the Texas Department of Highways and Public Transportation. The District covers thirteen counties and contains a total of 3271 miles of highways. Broken down in catagories there are 160.77 miles of Interstate, 1109.27 miles of U. S. and State highways and 2000.96 miles of Farm-to-Market highways. Total lane miles for this district is 8074. The age of all of the above highways necessitates heavy maintenance and most of them are in need of complete rehabilitation.

After funding for a project has been assured, we begin our design analysis by going to the project location and sampling all existing roadway material. I believe that our sampling technique is probably unique because in most cases we use a front-end loader and make a transverse cut across the pavement in each layer. These "samples" are transported to the District Lab and smaller samples are split from them for testing. This may seem crude to you but we have made errors in design procedures because our small (8 inch) core samples were not representative of the entire roadway. Also, I might add that the total roadway structure from the surface through the sub-grade is sampled and tested. We believe that you must know the characteristics of the existing material before you can properly design the new structure.

The designers' first rule is a District policy that we do not "waste" any material that we have purchased in the past. With this policy in mind we eliminate the urge to take the "easy" way out and dispose of all the existing structure or pile new material on top of the deteriorated surface. If laboratory tests prove the existing material to be completely inferior, then our laboratory technicians and design personnel recommend additives that can be used to upgrade the material to tolerable specifications. One good example of this is salvaged asphalt bituminous pavement. Rarely does it meet the requirements of asphalt stabilized base in this district but with the addition of approximately 30% virgin coarse rock and 3% new asphalt it becomes well within the requirements of that Item.

If economic studies prove that recycling is not practical, we ask the Contractor to stockpile the salvaged surface within our right-of-way. In doing this we are placing this material in a "bank" for later use in the adjacent area. I reiterate that no existing material is wasted on projects within our district boundaries.

Flexible base often does not meet the modern specifications. We have stabilized existing base with lime, cement, and asphalt emulsions. In some instances larger aggregate is added and on other projects new material is added and incorporated into the existing base.

One particular Farm-to-Market highway in this district was in very bad distress. The base was a pit-run silicious gravel. The surface ranged in depth from 1½" to 6", and consisted mainly of an accumulation of penetration seal coats and patches of various materials. There was evidence of sub-grade failures but the majority of distress was in the base and surface.

After design procedures were accumulated it was concluded that a whole new construction recycling concept would be used on this project. The entire base and surface was crushed, combined and stockpiled adjacent to the right-of-way line. The sub-grade was proof rolled and weak spots repaired by lime stabilization. The combined base and surface was picked up and placed through a Midland Paver where 6 percent, by weight, of CMS-2 emulsion was added and relaid in its original position. A one-course penetration seal was applied and the shoulders backfilled to complete the project. This project gave the State a 50 percent savings in funds and the construction time was reduced by approximately 75 percent.

All major Interstate rehabilitation is performed by full depth recycling on specification demand or the Contractor is given an option. If the Contractor chooses not to recycle, the salvaged material is stockpiled in a designated location to be utilized on another project.

One project on Interstate is underway at the present time. The Contractor who bid this project had a material source and a stationary hot-mix plant within an acceptable distance from the job. His bid was to remove the existing asphalt material and replace it with new asphalt stabilized base and surface. He has to stockpile all the salvaged pavement at a designated location very near a Farm-to-Market intersection. This FM highway has a good base structure but the surface is in very bad condition and the increased load limits dictate the need for additional strength. Our intention is to let another contract which will recycle the salvaged material and overlay the farm road with approximately 4" of recycled hot-mix.

In some instances complete full depth recycling is not feasible because of funding restrictions. When this type of construction is required, we try to arrange an overlay that will last as long as possible. One such project has been designed and completed near Abilene. The existing pavement was badly cracked and out of section, with evidence of moderate rutting. Our construction process was to profile the existing surface by Roto-Milling, place a 1" plant mix seal for a surface course. Since this raised the grade of the roadway, there was a need for shoulder material. Borrow for this type earthwork would cost us approximately $6.00 a cubic yard, in place. The Roto-Milled surface material had to be hauled to a stockpile location which would increase the cost of that item tremendously. It was decided that the existing grass shoulder should be bladed away from the roadway and the milled surface placed directly on the shoulder for shoulder material. We believe this to be both economical and also will conserve energy.

I think it should be clear to you by this time that every rehabilitation project that we have is related one way or the other to recycling. Yet, we insist that we do not recycle just for the sake of recycling. We have found after several years of study and practice that all existing material has some good qualities and minor modification can make a superior product out of roadway materials that appear inferior. There is no doubt in my mind that the time has come when every Highway Engineer is going to have to get more miles repaired with less people, less money, less virgin material, and less energy related materials. The only answer to this demand is to utilize every grain of existing roadway to the best advantage.

Table 1 (Jon A. Epps)

A. Basic Considerations for Project Selection

1. Type and amount of distress
2. Structural condition of pavement
3. Roughness
4. Traffic volumes
5. Skid resistance
6. Existing pavement cross section
7. Location and size of project

B. Comparison of Rural and Urban Project Selection Criteria

IITEM	RURAL	URBAN
Vertical control	Shoulders, bridges, safety appurtances	Utilities, drainage structures, safety appurtances
Traffic control	More options	Major problem
Road user costs	Do not always dominate costs	Dominate project costs
Time for construction	Not as critical	Critical
Size of project	Large projects because of move-in costs	Plants and equipment move-in costs minimal
Environmental quality	Not as many complaints on noise, heat, air quality, vegetation damage Permits to operate plants require up to 6 months to obtain	Critical but existing plants have permits
Aggregate and binder availability	Fixed and new sources	Fixed sources
Contractor availability	Most contractors prefer to work in rural areas	More competition
Existing pavement	Non-hard surfaced, thin surfaced	Thicker asphalt sections
Specifications	Lower quality materials Single project philosophy	High quality materials Multiple project philosophy

STATE-OF-THE-ART OF SURFACE RECYCLING

R. A. Jimenez, University of Arizona

The present knowledge and practice of asphaltic surface recycling is presented. A review of the available information has shown the practicability of restoring the desirable characteristics of pavement surfaces through the use of heater planer or scarifier processes. Also discussed are specifications for recycling agents and for construction procedures.

This report is concerned with a specific portion of the National Seminar on Asphalt Pavement Recycling. As indicated by the title, this presentation covers the topic of surface recycling as a review of the experiences and recommendations of those who have been involved in surface recycling principally in a restoration mode. Although some phases of present procedures of surface recycling have been performed, some 40 (1) or less years ago, the total process may still be considered as an art. Webster (2) defines an art as being a "skill in performance obtained by experience". However, the contributions of science to the successes of recycling cannot be disregarded.

The oil embargo of 1973 and other shortages in the highway construction industry gave an impetus and urgency to the reuse of materials in existing asphaltic roads for reconstruction or restoration of the roadway. Since the restoration processes are relatively new and have been practiced by various people over the country, a new jargon has developed and will be defined and summarized in the presentations of this seminar.

In general, recycling of pavement materials involves its transfer or moving to a processing area and then being returned to a/the roadway; thus completing a circuit. Recycling is practiced principally for economical reasons based on cost and availability of materials for making and processing pavement layers. Although not always so, recycling is concerned with the maintenance and restoration of an existing facility. (Asphaltic concrete from abandoned parking lots and roadways is being stockpiled for recycling into future pavements.)

The title of this presentation, Surface Recycling, indicates that the process involves reusing only the surface (top 1.91 to 2.54 cm [3/4 to 1 in.]), that its purpose is to restore or improve the road's surface condition, and that the recycling circuit (hauling distance) is very short. Some of the reasons for surface recycling are as follows:

1. To correct or eliminate surface deformations of rutting or shoving,
2. To correct or eliminate a slippery surface,
3. In correcting the above, to maintain the original elevation of the surface, and
4. To minimize reflection cracking to an overlay.

In the process of surface recycling, heat may or may not be used for breaking up the surface; new materials or modifying agents may be added; and the construction may be a continuous one-phased or a multiphased one.

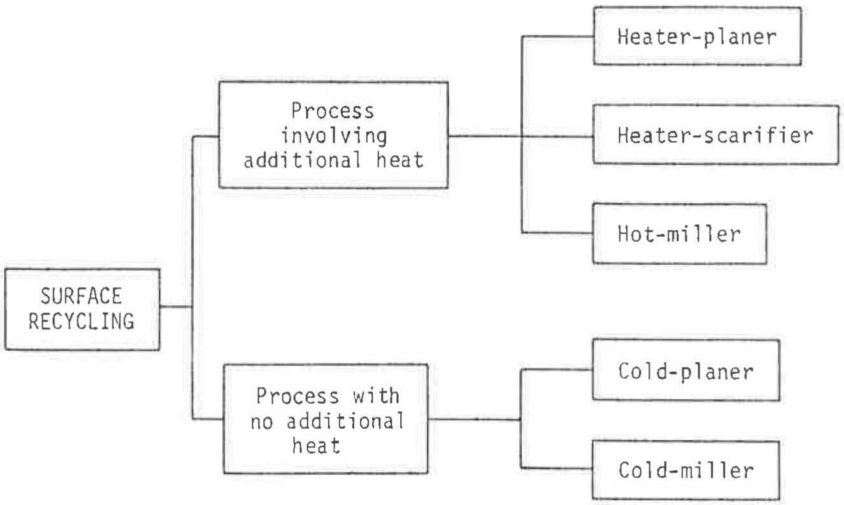
Prior to selecting a surface recycling-restoration program, preliminary investigations must be performed to establish the causes of the surface deficiencies and to show that surface recycling is a viable remedy. Subsurface weaknesses or failures in a pavement will appear on the surface as cracks or deformations. Shear failures of surfaces, bases, or subgrades will eventually appear as ruts at the surface. Fatigue or shrinkage weaknesses or failures in the pavement system will result in cracking of the surface. It is generally accepted that recycling for restoration of only the top 2.54 cm (1 in.) of the surface will not serve for a significant period of time before the existing failures recur. However, under certain conditions of age and moderate surface cracking, recycling of the pavement surface prior to an overlay is justified. The breaking-up of the old pavement surface destroys the crack pattern; the softening (low modulus of elasticity) of the recycled material will serve as a strain-attenuating layer; and the strengthening effect of the overlay; all contribute to minimize reflection cracking of the new surface course.

The design and construction of the recycled surface must be considered as carefully as for a new overlay. Thought must be given as to the effects of additives and construction procedures on the stability and bleeding characteristics of the recycled course, especially where more liquid is added to the recycled material.

Methods and Construction Procedures

There are two basic processes in use for the recycling of asphaltic pavement surfaces; one utilizes the heating of the pavement and the other does not. Figure 1 (1) presents a visual description of the

Figure 1. Basic surface recycling procedures.



processes and subdivisions for each.

From the third column of Figure 1, it is noted that the names of the processes are obtained from the type of equipment used. Accordingly, in defining the process using heat (1,3,5),

1. The heater-planer is a device that heats the pavement surface and then shears up to 2.54 cm (1 in.) of the hot material with a steel blade or plate,
2. The heater-scarifier is a device that heats the pavement surface and rips the surface up to a depth of 2.54 cm (1 in.) by raking spring loaded steel points over the hot materials, and
3. The hot-miller is a device(s) by which the pavement surface is heated and then miller or ground up to a depth of 5.08 cm (2 in.) with a rotating drum that has cutting tips mounted over the cylindrical surface.

As indicated earlier, this presentation is concerned principally with the restoration mode of recycling in which the material will be reused in the same pavement layer.

Cold Process

The cold-planing and cold-milling processes are used to remove surface material that is deteriorated or causes surface roughness or slipperiness. Although this material can be recycled for use in another layer of another pavement, it is not generally returned to reconstruct the original surface. It is to be pointed out that the material has not been reused for restoration principally because of the cold process itself.

Heated Process

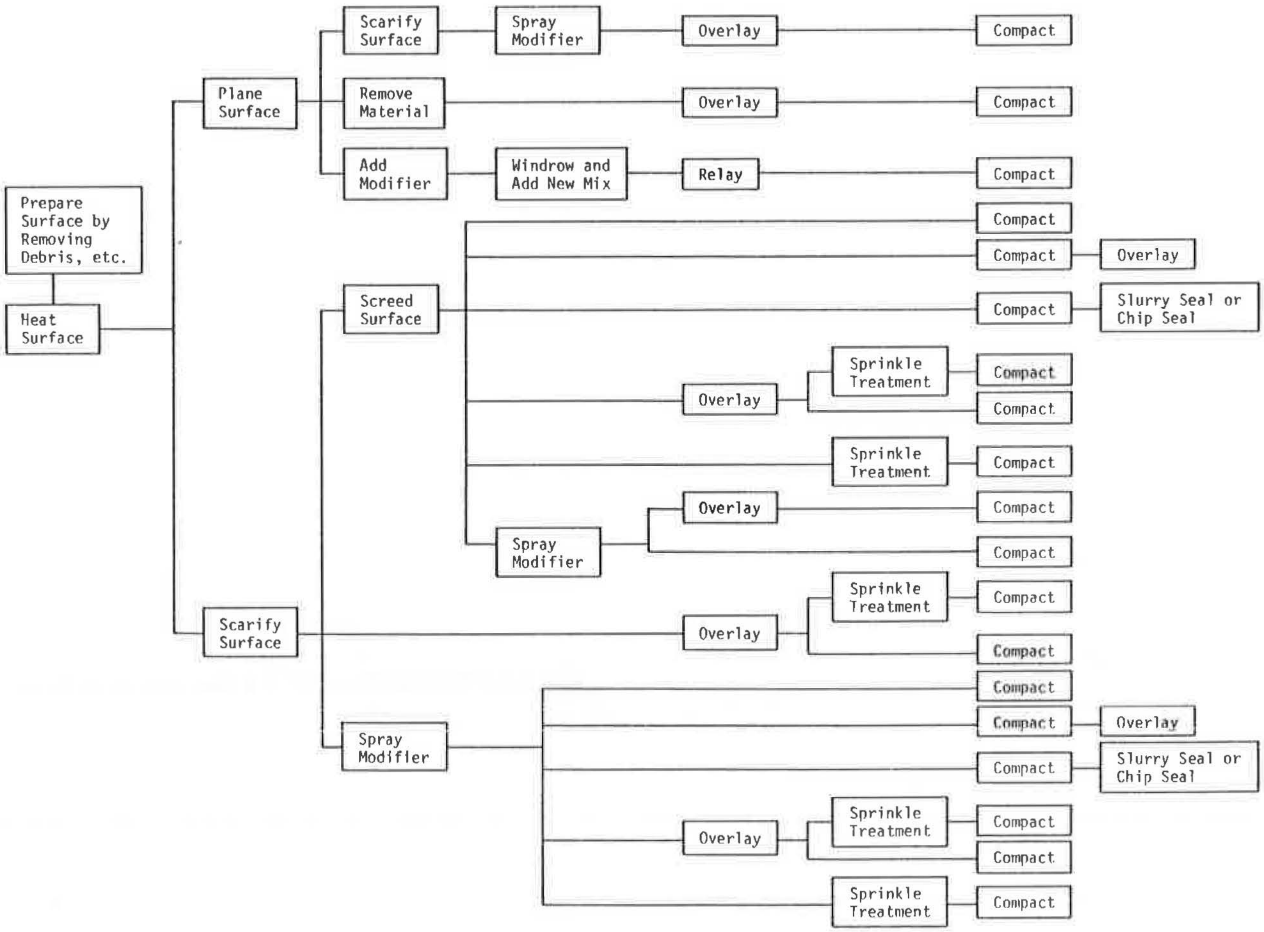
The several operations using a heated process of surface recycling are involved mainly with the reuse of the material in the surface. However, a form of the heated process is used for removal of surface material and for reuse elsewhere. Figure 2 shows the possible variations in the techniques available for surface recycling as suggested by Reference 3. It was not intended to give the objectives of the operations shown in Figure 2. The following paragraphs will describe procedures (1,3,4,6,7,8,9,10) that have been used to restore surface deficiencies by recycling or reclaiming methods.

To Correct a Slippery Surface. The pavement surface may have low skid resistance due to characteristics of the aggregate or to a bleeding or flushed condition. Analysis of the pavement and its surface material should guide in the selection of one of the procedures from the following:

1. a. The surface is heated and scarified,
   b. The surface material may be mixed for uniformity,
   c. A liquid recycling agent is sprayed, if needed,
   d. The recycled mixture is compacted,
   e. Skid resistant aggregate is spread,
   f. The aggregate and pavement is heated, and
   g. Steel wheel rolled to embed aggregate to proper depth.
2. a. The treatment of item (1) may be modified by adding and mixing new asphaltic mixture to the scarified material, and then spreading and compacting.
3. a. If the problem is a polished or nontextured surface,
   b. Skid resistant aggregate is spread over the surface,
   c. The aggregate and pavement is heated, and
   d. Steel wheel rolled to embed the aggregate.
4. a. The treatment of item (3) has been suggested for a flushed pavement surface; however, one must recognize that deformation may be imminent in such a situation.
5. a. If the existing material is not suitable for recycling into a surface course, then it must be planed and hauled away for possible reuse in some other location.
   b. The planed surface is then overlaid with a new mixture.

To Correct a Deformed Surface. The reasons for the rutting, shoving, or bumps must be established. Structural failures cannot be remedied with correction of only the upper 2.54 cm (1 in.) of the pavement surface. The following descriptions are related to possible treatments:

Figure 2. Surface recycling procedures using heat.



1. a. For a limited area of bumps or humps, the surface can be planed or heater-scarified,
   b. The excess material is used to fill the low or depressed areas,
   c. If necessary, liquid recycling agent is added,
   d. Then the planed and filled areas are compacted.
2. a. For the deficiencies or deterioration within a thin (3.81 cm [1 1/2 in.]) surface course, the layer can be removed by heater scarification or planing,
   b. Then a new surface is laid.
3. a. Under certain conditions the upper 2.54 cm (1-1 1/2 in.) of the surface can be heater scarified and mixed,
   b. If necessary, a liquid recycling agent is added,
   c. New asphaltic paving material is mixed with the old loose mixture, and
   d. Then the screeded and vibrated layer is compacted, forming a new layer generally less than 6.35 cm (2 1/2 in.).
4. a. If the existing material is not suitable for recycling into a surface course, then it must be removed for possible reuse elsewhere, and
   b. Then a new surfacing material must be laid.

<u>To Correct for a Cracked Surface</u>. An asphaltic pavement surface may be cracked for a variety of reasons. These reasons or causes can be generalized as due to shrinkage of the surface course, reflection of underlying cracks, failure by flexural fatigue, or construction shortcomings. Restoration of the surface generally requires recycling a position of the top course plus the addition of added asphaltic concrete or an overlay as described in one of the following methods.

1. a. The pavement surface is heater scarified,
   b. A liquid recycling agent is added,
   c. New asphaltic concrete is mixed with the reclaimed material,
   d. The new mixture is spread and compacted.
2. a. The pavement surface is heater scarified,
   b. A liquid recycling agent is added,
   c. The reclaimed material is spread and compacted,
   d. A new plant-mix overlay is spread and compacted.
3. a. The pavement surface is heater scarified,
   b. The scarified material is compacted,
   c. A liquid recycling agent is added,
   d. If needed, a flush or tack coat is added,
   e. A new plant-mix overlay is spread and compacted.

The original plus recent thinking on the successes of the above procedures is that (a) scarification breaks up the regularity of the surface crack pattern, (b) the recycled material plus the asphalt softening agent serves as a strain-attenuating layer to minimize relfection cracking, and (c) the recycled and new layer adds strength to the pavement by preventing surface water infiltration into the subsoils.

In addition to correcting surface failures described above, it is apparent that the processes of surface recycling and reclaiming can also be used for the purposes shown below.

1. To maintain curb height while repairing surface failures,
2. To maintain overhead clearance at overpasses while repairing surface failures,
3. To maintain, instead of adding to, the dead load on bridges while repairing surface failures.

Construction Equipment

A great variety of equipment for surface recycling has been used over the past years. For low volume farm-to-market roads constructed with liquid asphalts, the surface was planed or scarified and then recompacted to restore the surface smoothness. As can be imagined, blades, and disc or spring harrows could have been used. Development of some present day equipment has been regionalized and by people such as Cutler (6), Jackson (15), Payne (16) and Moench (17) for heater-planer scarifiers. Photographs of the various types of heater-scarifiers are shown in Figure 3. It is apparent from the size of these units that their operation and maintenance are quite involved and specialized. These units must be capable of heating the surface to a specific depth and within a certain range of temperature.

Controlled heating is necessary to soften the pavement for scarifying or planing without damage to the asphalt for reuse. Penetration of the heat into the pavement is tied to the speed of travel of the heater or heaters in tandem so as to leave a finite temperature gradient to the depth desired. Also, the heating of the surface must be such so as to minimize burning emissions and meet air pollution standards. In scarifying 1.90 to 2.54 cm (3/4 to 1 in.) of surface, a general requirement is that the temperature of the mixture behind the scarifier should range between 107-138°C (225-280°F) (9,12).

There are several methods used for heating the pavement surface. The fuel used may be a liquified petroleum gas (LPG) or diesel oil and the heating may be from an open flame or from a radiant tube for indirect heating.

A recent publication by V. Servas (22) describes a process developed by Wirtgen GmbH in West Germany for surface remixing. The procedure is similar to the U. S. practice except that the surface material is heated to temperatures between 140-160°C (284-320°F) and up to 8.0 cm (3.1 in.) can be heated and scarified. The pavement is preheated with a gas-fired, infra-red heater unit.

Costs of Surface Recycling

In some cases, certain operations of surface recycling may be subcontracted to specialists for heater-planing or scarification only. As a

Figure 3. Heater scarification in Arizona.

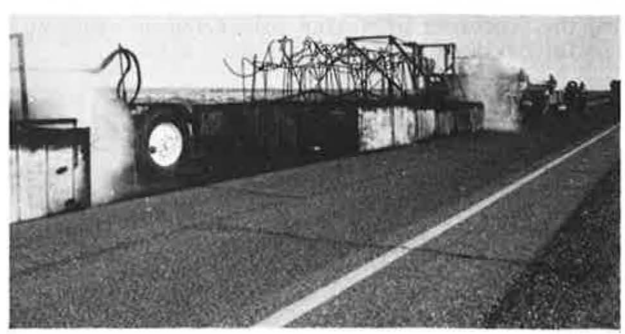


Table 1. Ranges of unit costs for surface recycling.

Item	Cost $/m	Comments	(Ref.)
Heater-planing	0.18 - 1.07	Removal of 1.9 cm	(12,18,19)
Heater-scarifying	0.30 - 0.95	1.9 cm. + additive, + compaction	(12,18)
a. plus 0.95 cm chip seal	0.95 - 1.67	Complete	(12,18)
b. plus 5.08 cm asphaltic concrete	3.09 - 4.76	Complete	(12,18)
Cold-milling	0.42 - 1.43	Removal of 2.54 cm	(18)
a. plus 90 kg asphaltic concrete	2.38 - 3.57	Complete	(18)

2.54 cm = 1 in.

0.84 m^2 = 1 yd^2

0.45 kg = 1 lb

consequence, and along with all the variables that affect bid prices, there is a wide range in the unit cost for surface recycling. The listings in Table 1 range in unit costs for various items in surface recycling.

The unit costs shown in the table were obtained from references dated 1980 and serve for immediate comparisons. The range in cost for a particular item, as shown, is based on difference in surfacings. The low cost operation would most likely be for a fine grained or soft surface; while the high unit cost would be for an old, hard, and 1.90 cm (3/4 in.) aggregate asphaltic concrete. According to Reid (19), one of the most important factors affecting cost of heater scarification is the depth of surface heating required in one pass of the equipment and meeting controls on temperature and air pollution at the same time.

Specifications for Surface Recycling

It appears that it has been the practice for specifications to be developed by promoters of specialized equipment to perform a particular operation or function. In some cases through ignorance or on purpose certain aspects required for an improved product have been omitted from the specifications. This does not imply that the specifications are not adequate, especially since a certain amount of flexibility should be afforded the contractor to incorporate more efficient methods or products.

In the Appendix, two specifications for surface recycling have been reproduced. One is that recommended by the Asphalt Recycling and Reclaiming Association and the other is one that was developed by the Arizona Department of Transportation following 12 years (10) of experience in surface restoration.

A review of the two recent specifications shows there are some variations in the methods for controlling the processes of heater scarifying or remixing. Examples of these differences are as follows:

1. One requires the heating unit to have a minimum rating of 10,584 MJ's (10 million BTU's) per hour and an hourly production of scarified material to be between 840-1,260 m^2 (1,000-1,500 yd^2); the other one does not set limits on heating capability or production rates,
2. One requires the pavement surface to be heated and remixed to a depth of 1.5 to 2.0 cm (0.6 to 0.8 in.); the other one controls the amount of scarification on the basis of 44 kg/m^2 (9 lbs/ft^2) to represent a scarification depth of between 1.90 to 2.54 cm (3/4 to 1 in.),
3. One does not mention weather or calendar restrictions; the other one does on the basis of project elevation.

Other than the three items listed above, the two specifications have much in common.

Recycling Agents

It is generally accepted that the asphalt on the surface of a pavement will age the most rapidly and to the greatest extent as compared to some lower location in the layer. This is to be expected since the highest temperatures and the most amount of air occur on the surface. In order to recycle the top 1.90-2.54 cm (3/4-1 in.) of the pavement for reuse as a surface cover, the asphalt must be returned or changed to have properties of an original asphalt. This transformation has been effected by incorporating liquid additives to the mixture being recycled. These additives have been called by various names such as asphalt-softening agent, asphalt rejuvenator, and recycling oil, and have been typed as being an asphalt emulsion, high penetration asphalt, or one of several proprietary materials.

A prototype specification was discussed by Kari (20) at the 1980 Annual Meeting of AAPT. Since at present there are no standards for specifying these materials, the basics of the Kari, et al., report will be discussed.

First, this class of material will be called "recycling agent" and defined as "A hydrocarbon product with physical characteristics selected to restore aged asphalt to the requirements of current asphalt specifications".

And secondly, specification tests and values are to be based on functional needs of:

1. Grade and consistency - viscosity
2. Handling and shipping - flash point
3. Volatility - oven weight change
4. Compatibility and solvency - saturates
5. Durability - viscosity ratio
6. Accounting - specific gravity

Table 2 (20) presents the suggested specification grades and test values for recycling agents. It is noted the recycling agents (RA) are graded from RA 5 to RA 500 on the basis of viscosity at 60°C (140°F).

Table 2. Proposed specifications for hot mix recycling agents.[a]

Test	ASTM Test Method	RA 5 min.	RA 5 max.	RA 25 min.	RA 25 max.	RA 75 min.	RA 75 max.	RA 250 min.	RA 250 max.	RA 500 min.	RA 500 max.
Viscosity @ 140°F, cSt	D2170 or 2171	200	800	1000	4000	5000	10000	15000	35000	40000	60000
Flash point, COC, °F	D92	400	-	425	-	450	-	450	-	450	-
Saturates, wt. %	D2007	-	30	-	30	-	30	-	30	-	30
Residue from RTF-C oven test @ 325°F	D2872[b]										
Viscosity ratio[c]	-	-	3	-	3	-	3	-	3	-	3
RTF-C oven weight change, ± %	D2872[b]	-	4	-	3	-	2	-	2	-	2
Specific gravity	D70 or D1298	Report		Report		Report		Report		Report	

[a]The final acceptance of recycling agents meeting this specification is subject to the compliance of the reconstituted asphalt blends with current asphalt specifications.

[b]The use of ASTM D1754 has not been studied in the context of this specification, however, it may be applicable. In cases of dispute the reference method shall be ASTM D2872.

[c]Viscosity Ratio = $\frac{\text{RTF-C Viscosity at 140°F, cSt}}{\text{Original Viscosity at 140°F, cSt}}$

The amount and grade of the recycling agent to be used for a particular pavement depends on the characteristics of the asphalt that one would require for new construction; that is, whether one would specify high or low viscosity of the asphalt. In order to determine the quantity of a recycling agent required, the pavement asphalt must be recovered and blended with varying amounts of the agent. Following the blending, the viscosity measurements would be made to pinpoint the amount of agent needed to give the desired viscosity for the new binder. Manufacturers of recycling agents have developed charts for obtaining the amount of recycling agent needed to obtain a specific viscosity or penetration value once the viscosity or penetration of the recovered asphalt is known. Kari, et al., (21) presented such charts and discussed the roll of recycling agents in hot-mix recycling.

Summary

The review for this state-of-the-art presentation has shown a lack of professional reports in the literature. Most of the information has been obtained from personal correspondence and promotional brochures. However, it seems evident that at the present the state-of-the-art of surface recycling is in transition into a well defined procedure that involves pavement evaluation, material evaluation, material proportioning, and construction controls.

Surface recycling has been used principally for conservation of materials and energy, and for reducing cost for correcting or minimizing pavement surface deficiencies of skid resistance, deformation, and cracking.

Future improvements to the present processes will most likely be in the equipment used.

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Appendix

A. Exerpts of a 1968 General Specification Covering Heater Scarification (13).

1. LOCATION

The work covered by these specifications is located on runway 30-12 and east apron and taxiway, Shafter Airport, Cawelo, California.

2. SCOPE OF WORK

A. Runway and Connecting Taxiway

The work to be done consists, in general, of heating, mixing and adding asphalt rejuvenating agent to existing surfacing and of surfacing with 3/16" minimum thickness slurry seal, as shown.

B. Taxiway and Apron

3. INSPECTION OF SITE

4. GENERAL REQUIREMENTS

5. SUPERINTENDENCE

6. EQUIPMENT

a. All equipment, tools and machines used shall be subject to the approval of the engineer as determined by their effectiveness in performance of operations to be accomplished, and shall be maintained in a satisfactory working condition while in use. Equipment not specifically meeting these specifications and rejected by the engineer shall be removed from the job site and replaced with suitable types.

b. The asphalt heater-scarifier shall be a self-contained machine specifically designed to reprocess upper layers of bituminous pavements. The machine shall be self-propelled, capable of operating at speeds of 0 to 70 fpm and consists of an insulated combustion chamber adjustable in width from 8' to 12' with ports permitting fuel and air injection for proper combustion. The heater shall have a minimum output of heat of 10,500,000 BTU per hour. The scarifier attachment shall be divided into sufficient sections individually controlled to conform with the existing pavement cross section, including inverted sections, and shall provide satisfactory protective devices to insure that no damage will be done to manholes, water valves or other existing structures. The scarifier shall be adjustable and consist of at least two rows of spring loaded rakes. Spacing of teeth shall be on 1-1/2 inch centers and the two rows shall be adjusted to provide maximum scarifying effect without ridging. The Contractor will be required to furnish a minimum of one 12-ton, 3-wheel roller or tandem roller; surface shall be rolled immediately following application of asphalt rejuvenating agent. Following the steel rolling, the area shall be thoroughly rolled with a rubber-tired roller.

c. Slurry seal shown on the plans shall be done in accordance with the State of California, Department of Public Works, Division of Highways "Standard Specifications" dated January 1964, Section 37, Bituminous Seals, Part 37-2, Slurry Seal, with the following exception: Only continuous pugmill mixer type equipment shall be used. Transit mix, or rotating drum mixers will not be used. Items 37-2.07 and 37-2.08 shall not apply.

7. GENERAL

The work will consist of preheating and scarifying existing asphalt surfacing in one operation which will be followed immediately with the addition of an asphalt rejuvenating agent and slurry seal application.

8. PREPARATION

Immediately before heating, the pavement shall be thoroughly cleaned of all dirt, debris, and loose material.

9. MATERIALS

The asphalt rejuvenating agent shall conform to the requirements for asphalt rejuvenating agent set forth in these special provisions.

a. The asphalt rejuvenating agent shall be composed of a petroleum resin oil base uniformly emulsified with water and shall conform to the following requirements:

Test procedure AASHO Designation: T59 to be modified by using distilled water in place of 2 per cent sodium oleate solution.

A test report shall be furnished in duplicate by the vendor at the time of shipment of each lot of asphalt rejuvenating agent. The report shall show the shipment number, date of shipment, contract number or purchase order number, quantity, and the results of the specified tests.

Before spreading, the asphalt rejuvenating agent will be cut back with water at the approximate rate of 33 per cent of water by volume, of the combined mixture. The asphalt rejuvenating agent mixture shall be spread at the rate of from 0.10 to 0.15 gallon per square yard of surface covered. The exact rate of application will be determined by the Engineer.

10. APPLICATION

a. The existing pavement shall be evenly heated and scarified to a depth of from 0.05 to 0.07 foot by a single continuously moving surface heater scarifier. The surface shall be left in an evenly spread condition and aggregate shall not be pulverized, spalled or broken. The minimum temperature of the scarified material shall not be less that 225°F. when measured three minutes following reprocessing. At least 90% of the aggregate shall be remixed by turning or tumbling. Following the scarifying operation, a cationic oil and resin emulsion, asphalt rejuvenating agent, shall be applied at the rate of .10 to .15 gallon per sq. yd. by a pressure distributor while the remixed material is still hot enough to cause demulsification. Overlapping applications of asphalt rejuvenating agent and leaking of the pressure distributor spraybar will not be allowed.

b. The spreading of slurry seal as specified in these special provisions shall follow after surface is rolled to engineer's satisfaction.

11. AIR TRAFFIC CONTROL

12. CLEAN UP

Upon completion of the job, the site shall be cleaned of any paving material, oil matter, and debris caused or left over in the process of this work.

13. GENERAL SPECIFICATIONS

This Contractor shall provide the Engineer with sieve analysis reports of the aggregate and emulsion weigh slips.

14. TRAFFIC CONTROL

This Contractor shall work in close cooperation with the Airport manager. Runways 30-12 shall be "X"'d out or closed as per plan for the duration of application and curing time of this project.

B. Asphalt Heater-Scarifying or Remixing (4).

SCOPE

This item shall be part of a multi-step process of asphalt surface rehabilitation that consists of softening the existing flexible pavement with heat and thoroughly stirring, spinning or tumbling the mixture; applying an asphalt rejuvenating agent; and installing a surface treatment or overlay.

The operation shall be planned so as to be safe for persons and property adjacent to the work, including the traveling public (the route may or may not be kept open to traffic during construction).

The contractor shall take such additional precautions as he deems reasonable for the safety of his operation.

EQUIPMENT

The equipment for heating and scarifying shall be of a type that has operated successfully on similar work completed prior to the award of this contract or equipment proven through test results.

The heating unit shall have a minimum rating of 10,000,000 BTU's per hour. The hourly production of heated and scarified material shall be between 1000-1500 square yards per hour. The heater scarifier may be equipped with a leveling device to provide for an even distribution of loose material. The scarifier shall be of a type to insure continuous and undiminished pavement contact without damaging manholes and valve boxes. Overhanging trees shall be trimmed in advance to a 9' minimum clearance. Parkway trees may be protected from heat damage by individual shielding and water spray or any combination the contractor deems practical.

SURFACE PREPARATION

The pavement surface to be heater scarified shall be first cleaned of trash, debris, earth or other deleterious substances present in sufficient quantity to interfere with the work to be performed.

HEATING AND SCARIFYING

The pavement surface shall be evenly heated and remixed to a depth of between 0.5 to 0.7 foot (.0155 to .0127m) by a continuously moving surface heater scarifier machine. At least 90% of the aggregate shall be remixed by spinning or tumbling. Heater material shall have a temperature in a range between 220 degrees - 260 degrees Fahrenheit measured immediately behind the heater scarifier. The remixed layer shall be uniformly and evenly heated throughout. No uncontrolled heating, causing differential softening of the upper surface will be permitted. The asphalt binder shall not be carbonized in excess of .10 of one percent. The scarified material shall be left in an evenly spread condition. Aggregates shall not be pulverized, spalled or broken. Width of scarified surface shall be sufficient to accommodate subsequent processing.

NOTE: When the surface to be scarified is to have an overlay of new pavement placed thereon, the scarified material adjacent to any concrete structure can be shaved or graded to provide a uniform cross-slope. The excess material may be distributed and compacted as a leveling course over the adjoining scarified surface or removed from job site depending upon the finished grade design contour. Excess material or oversized aggregate dislodged by the planing or remix operation too large to be covered by the overlay, shall be removed and disposed of by the contractor at his expense.

ALTERNATE

A standard header or gutter cut should be normally performed prior to heater scarifying. The excess material is loaded and hauled to a site for reuse off the project. In the event a 1" or greater depth of cut is required, the planing or removal operation should be scheduled first as the speed of performing it is generally slower than heater scarifying.

LEVELING DEVICE

Following the heater scarifier and before overlay installation, a leveling device reduces ridge buildup present from heavy scarification of soft mixtures. Material processed by the leveling device should be monitored to assure leveling of grooved and loose stike-off.

ALTERNATE - SCREED DEVICE (for special situations)

Following scarification and before compaction, if a surface treatment has been specified, an oscillating or vibratory device shall spread and distribute the loosened mix. Rolling may be required to compact oversized aggregate and finish the mat closing the voids.

Contractor shall furnish the services of a registered professional engineering laboratory specializing in asphalt technology. Abson recovery tests shall be made on representative cores prior to construction to obtain asphalt penetration (ASTM D-5) and to determine results of treating binder with variable types of additive. No work shall be undertaken until the laboratory report has been approved by the Engineer.

The cost of testing and preparation of reports shall be included in the cost per square yard for heating and remixing surface. The number of cores required shall not exceed 1 per 10,000 square yards of treated pavement.

Contractor shall minimize the escaping of particulant into the air by either the machine or burning of pavement during the heater remix operation. The machine shall be operated to conform with standards of the Air Pollution Control District.

ASPHALT PRIMER

An asphalt primer shall be applied at the rate of .1 to .25 gallon per square yard by a pressure distributor at the end of each work shift. The primer may be scheduled to be applied in one continuous operation to obtain uniformity and prevent overlapping.

PRIMER ALTERNATIVES

Primer--Type 1

The asphalt rejuvenating primer shall be composed of a petroleum resin oil base uniformly emulsified with water and shall conform to the following requirements:

Specification Designation	Test Method	Requirements
Viscosity, S.S.F. at 77°F, Seconds	AASHTO T59	15-40
Sieve Test % Max.*	ASTM D244-60 (Mod)	60
Particle Charge Test	Calif. 343A	Positive
Tests on Residue from ASTM D244-60 (Mod)		
Viscosity, cs. 140°F	ASTM D445	100-200
Asphaltenes % Max.	ASTM D2006-65-T	0.75
Ratio $\frac{N+A1}{P+A2}$	ASTM D2006-65-T	0.3-0.5

*Test procedure identical with AASHTO T59 except that distilled water shall be used in place of 2% oleate solution.

Primer--Type 2

The asphalt primer shall be composed of asphalt cement uniformly emulsified with water and shall conform to the following requirements:

Specification Designation	Test Method	Requirements
Viscosity, S.F. at 77°F, Seconds	AASHTO T59	20-100
Residue, % by wt.		57-62
Tests on Residue per 77°F 100g 5 sec.	AASHTO T49	100-200
Ductility 77°F cm	AASHTO T51	40+

Primer--Type 3

The asphalt rejuvenating primer shall be composed of a 50/50 blend of petroleum resin oils and asphalt emulsified with water and shall conform to the following requirements:

Specification Designation	Test Method	Requirements
Viscosity, S.F. at 77°F Seconds	AASHTO T59	12-25
Residue, % by wt.	Calif. 351	50-65
Particle Charge Test	Calif. 343A	Positive
Viscosity, cp, 275°F	ASTM D445	20-65
Asphaltenes, % Max.	Calif. 352	9-13

DISTRIBUTOR

The distributor should also comply with specifications. While spraying, the pressure should be high enough to give the desired application through uniform spread along with constant straight edged spray fans at each nozzle. The spray bar should be at a constant height to prevent streaking.

ROLLERS

The use of self-propelled smooth tread pneumatic tire rollers is recommended on surface treatments so that the aggregate is imbedded firmly into the asphalt without crushing the particles. In general there are three types of rollers which may be used to compact heater scarified treatments. A pneumatic tired roller or steel wheel roller should be in a range of 10-12 tons overall.

The vibro roller is a unique tool which is capable of achieving very high density with only a few passes over the surface. The vibrating effort of the roller is controlled and produces density without causing horizontal displacement. The steel wheel and vibro roller may be used effectively on surface of uniform grade without abrupt breaks at the quarter point or crown. If a surface is distorted, a satisfactory result is obtained by specifying the pneumatic tire roller.

The multi-step process should be kept as close together as practical to insure the maximum benefit is achieved from each phase for complete integration and to permit easy traffic arrangement.

MEASUREMENT AND PAYMENT

Heater Scarified - Heating and scarifying treatment will be measured by the square yard or square meter and shall include all work completed and accepted.

The accepted quantities of heating and scarifying treatment will be paid at the contract unit price per square yard for heating and scarifying treatment. Testing and preparing reports prior to treatment of pavement shall be included in the unit price per square yard or square meter. Surface regrading or leveling course constructed as described in the plans and specifications, including all operations of planing and compaction shall be included in the unit price per square yard or square meter and no additional payment will be made.

Alternate - The asphalt pavement adjacent to gutter is to be planed or removed in the form of a wedge 5' to 6' wide to desired depth as a separate operation. The linear feet of cut will be measured and shall include all work to cut, load, haul material for reuse, and sweep surface as directed by the Engineer.

The accepted quantity of gutter cut will be paid at the contract unit price per linear foot for performing all work.

Asphalt Rejuvenating Agent - is paid for by weight and shall be weighed on sealed scales, regularly inspected by State Bureau of Weights and Measures, or may be measured in some other approved manner. A load slip shall be delivered to the Engineer at point of delivery of their material. Asphalt concrete overlay required shall not be paid for under this section.

C. Recycling of Existing Bituminous Surface (14)

DESCRIPTION:

The work under this item consists of recycling the flexible pavement. It shall be accomplished by heating, scarifying, remixing, releveling, compacting and rejuvenating the existing bituminous surfacing material.

EQUIPMENT:

The equipment used to heat and scarify the bituminous surface shall be fueled by liquified petroleum gas. It shall fully meet the standards of the Bureau of Air Pollution Control, Division of Environmental Health Services, Arizona Department of Health Services.

One pneumatic tired compactor shall be furnished to compact the scarified material; however, in addition to the pneumatic tired compactor, the contractor may furnish any other type of compactor. Pneumatic tired and tandem power (steel wheel) compactors shall comply with the requirements of Subsection 406-3.05(F) (2) and (3) respectively of the Standard Specification.

CONSTRUCTION DETAILS:

The work shall generally be accomplished only between the dates hereinafter shown as applicable to the average elevation of the project; however, the beginning date may be moved ahead and the ending date may be extended if, in the opinion of the engineer, weather conditions, surface temperatures and other factors will not have an adverse effect upon the work. At any time the engineer may require that the work cease or that the workday be reduced in the event that weather or other conditions will have an adverse effect upon the work.

Average Elevation of Project, Feet	Beginning and Ending Dates
0 - 3499	February 15 - December 15
3500 - 4999	April 1 - October 31
5000 and Over	May 1 - September 30

Prior to commencing heater-scarifying operations, the existing pavement shall be cleaned of all extraneous material. Power brooming shall be supplemented, when necessary, by hand brooming until all deleterious material has been removed from the existing surface.

The number of heater units utilized shall be determined by the contractor; however, if all heater units are equipped with scarifiers, only the scarifier on the last heater unit of the series shall be utilized for scarification. Multiple heater units shall be utilized in tandem such that the heat emitted and the rate of travel will achieve the specified requirements.

The existing bituminous surface shall be heated not less than six nor more than 12 inches wider than the width of the material to be scarified. The temperature of the scarified material shall be not less than 200 nor more than 300 degrees F. when measured immediately behind the scarifier.

The weight of the existing bituminous surface has been estimated to be approximately 144 pounds per cubic foot. On this basis, a minimum of nine pounds per square foot of the existing bituminous surface shall be scarified for a depth betwen 3/4 inch and one inch of unscarified material. If tests indicate that the material weighs either less than 137 or more than 151 pounds per cubic foot, the pounds per square foot to be scarified will be adjusted accordingly by the engineer.

If the specified amount is not being scarified after the first full hour of operation, the work shall be stopped and shall be resumed only after adjustments have been made by the contractor which will satisfy the engineer that the requirements can be met.

The scarified material shall then be processed by mechanical equipment equipped with an operating vibratory or oscillating screed capable of producing results approximating those obtained by an asphaltic concrete laydown machine. The equipment shall effectively distribute and level the material to a width no greater than the original width of the material scarified. The equipment may be a separate unit or it may be attached to or be a part of the scarifying equipment. Any equipment deemed to be producing unsatisfactory results will be rejected by the engineer.

The bituminous surface shall be compacted immediately after it has been distributed and leveled and while it is still hot.

Within 30 minutes after compaction, the rejuvenating agent shall be applied; however, no material to which the rejuvenating agent has been applied shall be reheated and rescarified.

If the engineer determines that excessive ravelling has occurred, he may direct the contractor to apply Emulsified Asphalt (Special Type) to the scarified material. The application rate will be specified by the engineer.

ACCEPTABILITY OF SCARIFICATION:

Scarification will be deemed to be acceptable when the moving average of a minimum of three consecutive random tests per hour indicates that the required amount per square foot, based on the weight per cubic foot, of the existing bituminous surface has been scarified.

The amount of material scarified will be determined in accordance with the requirements of Tentative Arizona Test Method 409.

The weight of the existing bituminous surface will be determined in accordance with the requirements of AASHTO T-166 from scarified material compacted in accordance with the requirements of AASHTO T-245, with the exception that the compaction temperature shall be 240±5 degrees F.

METHOD OF MEASUREMENT:

Measurement of this work will be made by the square yard of bituminous surface scarified.

BASIS OF PAYMENT:

Payment for this work will be made at the contract price a square yard for ITEM 4060701 - RECYCLING OF EXISTING BITUMINOUS SURFACE, which price shall be full compensation for the item complete, as herein described and specified.

No adjustment in the contract unit price will be made if tests indicate a weight per cubic foot of the existing bituminous surfacing differing from that shown hereinbefore and the amount of material to be scarified is adjusted accordingly.

Rejuvenating Agent for Bituminous Surface Recycling will be measured and paid for under Item 4012311.

Emulsified Asphalt (Special Type) will be measured and paid for under Item 4030001.

URBAN SURFACE RECYCLING

Gordon F. Whitney, P.E., G.J. Payne Company

Over the past decade, pavement construction and maintenance costs have more than doubled while public works budgets have remained relatively constant, sometimes even decreasing. The escalating rise in new street construction and maintenance cost is a direct result of the current OPEC situation, our dependence on foreign oil and the correlation between asphalt and crude oil product prices. Today's Public Works Engineer has fast become maintenance oriented, as he should be. A major concern must be one of increasing the strength and serviceability of existing streets, while adhering to the necessity to economize. The more expensive method of restoring a worn flexible pavement by resurfacing with a strengthening overlay is now often revaluated in favor of surface recycling and applying a seal coat to waterproof the underlying pavement structure.

The idea of recycling pavement sometimes evokes fears that the recycled material may not possess satisfactory quality and will soon fail under traffic loading. Great improvements have been made in quality control, particularily over the past several years, to eliminate uncertainty and upgrade the end result. Work performed using new "Arizona" specifications and Asphalt Recycling and Reclaiming Association (ARRA) standards (1) with rigid inspection bears no resemblence to earlier heater scarifying work. The technology for successfully recycling asphalt pavements has already been developed and is now available to engineers for more extensive usage on urban projects.

Pavement Evaluation

A pavement study to establish a properly budgeted, long range maintenance program is the primary step frequently taken by Public Works Engineers. An ongoing street evaluation program should provide that in each successive year, certain streets previously studied will undergo additional testing. Successive repetitions will permit the establishment of accurate "rates of change" curves. With additional inputs of data, it is possible to accurately program the type, amount and cost of future maintenance, and determine which pavement design, construction method of maintenance technique provides the most economic service to the community.

Corrective procedures may be developed after considering roadway sufficiency, serviceability, structural adequacy and physical conditions of pavement materials. Investigations should include deflection testing, field and laboratory testing of pavement and base materials; correlation of field date with historical design and construction information; reviewing maintenance records and traffic loading and analyzing the information gathered to prepare recommendations.

Recommendations vary from immediate routine maintenance to extensive repairs by means of a program of resurfacing, reconstruction, seal coating, surface recycling or some combination of these to treat existing surfaces and establish priority schedules for each, based on need, with programmed reviews for updating the priorities. This report will focus primarily upon the maintenance procedures involved in surface recycling.

As might be expected, virtually all streets possess some deficiencies that merit maintenance attention. This maintenance may be of major or minor consequence, but failure to correct a deficiency will lead to further deterioration and increased maintenance costs.

Frequently, streets are structurally sound and not in need of improvement insofar as the pavement section is concerned. There may be deficiencies in the pavement materials which will lead to deterioration of the surface and ultimate structural failure, but which can be corrected by proper preventative maintenance.

Many pavements possess highly embrittled asphalt binder and failure to correct this condition will lead to deterioration of the pavement and ultimate structural failure. The asphalt aging phenomenon occurs frequently in the Southwestern United States and is aggravated by the climate, quality of petroleum crude used to produce the asphalt matrix and many other complex ecological and little understood factors.

Deflection Testing and Analysis

An important predesign study is the determination of present structural condition as compared to its original design strength. The deflection testing is often conducted using the "Road Rater" which is a hydraulic test apparatus that determines the pavement's strength by non-destructive means. The machine, with warning devices, is fast moving and allows traffic to pass with very little delay or interruption and no significant congestion. The Benkleman Beam may also be used, but does not equal the former's speed for data collection.

Asphalt concrete overlay requirements are determined by measuring surface deflections resulting from imposing a known combination of static and dynamic loads and relating this to the strength or load carrying ability of the "in-situ" material.

Generally, the greater the deflection, the lower the strength of pavement. Thin pavements are relatively more flexible and permit greater deflections than thick pavements. An exception to this generalization could occur with an older pavement with diminished asphalt viscosity value due to aging. It may give the appearance of strength when, in fact, its rigidity indicates the approach of brittleness, cracking and failure.

Pavement Samples

Sufficient cores are taken from problem pavements to reveal the make-up of the structural section, with data from city records to frequently supplement and verify the findings.

Results afforded by laboratory analysis of the pavement core components are important in understanding the reasons for pavement distress. The laboratory should determine the percent of asphalt in the pavement surface layer, its viscosity and the density of the entire asphalt concrete pavement layer.

Pavement Materials

Although some streets are structurally weak, much of the visible distress can be directly attributed to physical deterioration of the pavement itself. Laboratory analysis (2) of the representative samples extracted from roadways reveal that most pavements have asphalt binder that has become highly embrittled. It is also observed that many areas exhibiting extensive alligator type crack patterns are not structurally weak, thus eliminating load associated reasons for failure.

Non-load associated distress sometimes is the result of thermal cracking of asphalt binder which has lost its viability and reflective cracking of underlying Portland Cement Concrete joints and failures. The inability of a pavement to withstand movement whether due to temperature induced expansion-contraction cycles or the movement of underlying slabs, increases as the asphalt binder hardens and ductility is lowered.

Research

A proper evaluation of streets requires extensive knowledge of design, construction and maintenance. Plans and reports should provide design "R" value and Traffic Index, street construction specifications and maintenance history. Additionally, "R" value and construction data may be obtained from County Road Departments and the State Division of Highways.

Condition surveys document distress and street deficiencies, as observed during many trips over city streets. Adverse conditions such as cracks, raveling, bumps and roughness result from failure or deficiencies in the pavement and can be correlated with deficiencies reported by the various testing procedures. Such reviews are often made by city engineering and maintenance personnel and provide information that, when combined with test results and other data gathered, permit development of recommendations.

Historical Recycling Background

Modern surface recycling originated in a process which began in the 1950's. Gibbons and Reed Contractors of Salt Lake City developed early heater planers, utilizing the motor grader chassis equipped with a small combustion chamber. They built and improved these tools which were used throughout the Western United States to remove irregularities and instabilities from asphalt pavements.

Gradually, larger more complex machines evolved which were able to heat, cut and load the upper layers of the asphalt pavement. Increased depth requirements for planing were satisfied by repeatedly cutting the surface one half inch at a time until the desired grade was achieved. The machines often caused visible emissions due to variations of the asphalt content in the pavement being processed. Crack pouring material, transmission oil dripping and paint on the surfaces aggravated ecological problems with the public. The relative hardness of old asphalt pavements and the need to maintain a constant temperature in a combustion chamber (subject to wind and variations of the burner draft) made the heater planer a very difficult machine to operate within stringent pollution standards. The slow production of these machines contributed to high cost of removing deep layers, and heat escaping from the burner to adjoining trees and shrubs caused damage while wasting fuel and energy. The loosened asphalt mix material produced by heater planing could be reclaimed when still hot, which meant that it was only possible to reuse and compact within a short distance of the planing project.

Heater scarifying, or remixing, developed by modifying heater planers with scarifier rakes to probe the surface which had been heated. As burner designs continued to improve, machines were able to penetrate a uniform thickness causing only minor visible emission.

The economic reason for surface recycling (scarifying and rejuvenating) was to relevel the surface and eliminate the cost of transportiang asphalt materials to other locations when it might be utilized on site. The use of cleaner, low sulfur fuels improved the general performance of these machines, although it was a process which had to be closely controlled by the operator when using only one machine.

Surface Recycling Advantages

On certain projects, heater recycling can offer significant improvements to conventional overlays, as well as prepare a surface for receiving thin overlays, chip or slurry seal treatments (3).

> Because of the roughened texture caused by the scarifier teeth and elevated temperature of the new asphalt mix placed as an overlay, a bond develops at the interface of new and the existing asphalt layers. This means the resurfacing shows greater resistance to deflection and shear than an overlay installed upon a conventional tack coat.
>
> As a result of heat and the re-arrangement of aggregate particles by scarification, reflection cracks through a thin overlay or seal coat will be minimized.
>
> Pavements exhibiting moderate surface distortion are leveled by the rakes to receive a uniform thickness overlay or seal treatment without a separate and costly planing operation.
>
> When surface treatments or thin overlays are programmed, raw material is conserved and drainage capacities of curb and gutter are retained

longer. More miles of street may be treated due to low cost of surface recycling.

Analysis

Surface recycling can only correct certain defects. Asphalt pavements exhibiting minor corrugations, alligator cracking, raveling, polished aggregate, or bleeding are all candidates for the process. On the other hand, if the distress results from an inadequate base and shows up in pavement failure, pot holes, upheaval, or severe rutting, extensive base reconstruction must be considered.

As the technology improved, it was determined that if a pavement temperature is increased slowly, in steps, using multiple machines, the pavement would never reach a temperature to emit particulate. In some instances, cold planing was required to first remove any imperfections or contaminates which have accumulated on an asphalt pavement and which might produce emissions. E.P.A. standards and maximum permissable limits for emissions may not be exceeded. A current requirement of the South Coast Air Quality District covering the Los Angeles Basin, one of the country's most sensitive ecology areas, is to be found in Appendix B.

Today's operation for high quality work (4) is monitored by removing a known volume of scarified material to weigh and determine specification compliance. The design engineer can now specify a weight per square foot of recycled material just as he would when purchasing a new asphalt concrete material. The recycling agent application is also closely controlled after laboratory tests indicate the type and amount of agent needed to renovate or rejuvenate the asphalt binder. When treating deep lifts of surface recycled material, the loosened mix is generally struck off by a screed, then compacted while still at an elevated temperature and the recycling agent is applied uniformly at the end of the work shift. A thin overlay of new asphalt concrete, or a seal coat, is installed sometime later to complete the process. The basic reasons for utilizing surface recycling are:

1. Pavement rehabilitation. Here the depth of scarification is of major importance and the contractor and engineer should endeavor to achieve the maximum depth of penetration from the rakes. This should be done with care to insure the asphalt cement binding material in the treated layer is not damaged or destroyed by over application of heat.
2. Surface preparation for a strengthening overlay. Frequently specified for airport and highway construction. Recycling functions to insure the existing surface does not possess contaminants, such as paint stripes, fuel and oil drippings or rubber tire impact marks. The necessity for load transfer from the new overlay to the old is extremely important and adds to the structural value of an overlay. It is thought that this may be due to the mechanical keying action, but may also be a result of addition of the recycling oil which greatly enhances the performance characteristics of aged asphalt binder in the original pavement.

Methods of Recycling

There are two methods of performing surface recycling, i.e., the paving train method and the two stage technique (5). The paving "train" came first and involved pretreating the surface and installing an overlay at the same time in a coordinated operation. This "train" consisted of a heater scarifier machine, oil distributor and conventional paving equipment. All operations are programmed to be performed within a distance of 700 feet. The coordination of such a paving operation and the difficulty in applying a uniform spread of asphalt recycling agent on the treated surface led innovators to develop other methods of installing the surface. The two stage method is more frequently used today and separates the paving operation and surface recycling crew.

Heating

In either case, the process consists of passing one or more machine-mounted high intensity heaters over the surface to be repaired at a speed which will allow the distressed material to be softened. This speed varies widely, depending on several factors. Typical speeds range between 1.5 and 15 m/min (5 to 50 ft/min). The heaters should bring the surface asphalt to a temperature somewhere between 110 to 150°C (230 to 300°F) with the ideal temperature generally in the 125°C (250°F) range during the compaction process. Although much argument and discussion has been directed toward the terms "radiant" and "direct" heating, there is little supporting evidence that any one machine is superior to another in raising pavement temperature. The time of exposure of a constant heat source will cause an elevation of temperature in direct relationship and two machines or more will develop a uniform rise of temperature in the recycled layer without harm to the binder.

Care should be exercised to avoid charring the pavement which may damaged the asphalt, resulting in undesirable visible emissions. This can be avoided by either reducing the burner combustion heat or increasing the equipment rate of travel. The temperature may be verified or measured by mounding the scarified mix and inserting a thermometer as with conventional new paving material.

Scarifying

A scarification depth of 19 mm or 3/4" minimum is recommended; and as mentioned, for certain types of pavement, multiple heaters may be necessary to allow the heat to penetrate a seal coat. When multiples are used, the first preheats only to raise the temperature, while the last machine heats and scarifies the pavement.

Equipment Improvements

1. Extended length, high reflective combustion chambers (16-30 feet) insure deeper heat penetration.
2. Improved down pressure on scarifier rakes with stronger rake assemblies improves operation.
3. A heavier power train facilitates scarifying.
4. Better combustion is achieved with LPG fuel for cleanliness in a lightweight refractory oven.
5. Dual operator controls help.

Applying Recycling Agent

The process of pavement aging or oxidation consists of a chemical reaction which slowly changes the characteristics of the asphalt cement. The effect of this change is a gradual embrittlement of the pavement (6). An oxidized pavement usually appears gray, dried out and dull.

The theory for surface recycling is based on the fact that oxidation occurs most rapidly at the surface, which is in contact with the elements. The surface may have lost some of its resiliency and perhaps has begun to show cracking; while underneath the asphalt binder is relatively unaffected by its environment and in nearly new condition. Studies reported by Coon and Wright (7) indicate no change in relative viscosity of binder below 3/4" level on pavements 4 to 151 months of age.

Chemical additives, called recycling agents, have been developed which reverse this oxidation process by restoring some of the lost constituents, and in so doing, replasticize the asphalt cement. The selection and application of one of these liquids is an important step in surface recycling.

Some agents are proprietary recycling agents, while others are emulsified asphalts which are usually applied using a distributor truck. The agent should be applied at the highest temperature recommended by the refiner to permit even distribution throughout the loosened material.

Testing

The amount of recycling agent to be applied to the scarified material layer is determined prior to beginning work. This is done by removing three or more six inch diameter core samples from the structure for testing in a laboratory (8). One core is tested as is to determine the viscosity and ductility of the existing asphalt in the top 3/4". The other two are heated, scarified to a depth of 3/4", then 0.1 gsy of recycling agent concentrate is pread on one core and 0.2 gsy on the other. These cores are then placed in a 140°F oven for a minimum of three days, after which the asphalt is extracted from the top 3/4" of each core and tested. The quantity selected is mathematically added to the existing asphalt percentage to determine feasibility of improving the binder qualities without overasphalting the layer. Regardless of the type of recycling agent used, the same type of test can be performed to first ascertain the lowering of viscosity obtained from using a specific additive and then compare various agents available to treat a hardened asphalt cement. Field adjustment should be made by the inspector when it is apparent that there is a discontinuity in material or that the indicated laboratory amount is causing either a deficiency or excess of oil.

Asphalt Pavement Overlay

Generally, in the "train" mode, a standard overlay follows surface recycling as soon as practical. It takes but a few minutes for the remixed material to cool to ambient temperature, but the new mix arriving on the job at 270°F reheats the loosened material, welding the surface together. A closely spaced operation can cause difficulties in that large construction equipment (heater scarifier, distributor truck, haul trucks, asphalt paver and rollers) is concentrated in a relatively small area. Coordination of the equipment to function smoothly can be a problem. If it is not possible to achieve an even oil spread application or coordinate recycling equipment production with paving material, it may be advisable to adopt two stage operation.

The thickness of the pavement overlay chosen depends upon the purpose of the recycling. If the primary goal is to rejuvenate the upper layer of existing material and improve the riding qualities of the street that is structurally adequate, a minimum thickness will suffice. This minimum thickness depends mainly upon the gradation of aggregate in the new mix. As a general guide, the overlay thickness should be no less than 1.5 times the maximum particle size in the new mix.

Crack Prevention

The pavement overlay mix design selected to cover the recycled surface requires consideration of its function. In areas of sparse rainfall where existing pavements show signs of actinic aging, an open graded plant mix is extremely effective. The wide shrinkage cracks common in desert regions due to the drying out of the pavement, render the surfaces rough. During cold weather, wind blown materials often fill the open cracks preventing them from closing during the warm season which causes an extruded bump on either side of the crack. The open graded plant mix fills the crack and the heavier asphalt film on the aggregate keeps the crack from reappearing in the finished surface. This improves the appearance and riding qualities of an otherwise difficult pavement for a much longer duration of time.

Waterproofing Structure

In other sections of the country, a dense graded asphalt plant mix is chosen for its waterproofing qualities to prevent snow and moisture from penetrating the subgrade and softening the entire structure. Should alligator cracks indicate a diffused or even distribution of stresses in the existing pavement, the addition of a conventional dense graded plant mix overlay will improve the structure and provide years of continuous service.

Heavier Load Service

If the primary purpose of resurface/recycling is to increase the structural capacity, the overlay should be designed according to conventional procedures to yield the required strength. While each project must be analyzed for its specific needs and thickness of new asphalt to be placed, it generally is placed at 1" minimum thickness; however, the upper limit can range from 2 to 4" depending upon the improvement to the structural section that may be required.

Variations of the Procedure

Frequently, the sequence of operations in the paving "train" method recycling is reordered. The steps in the two stage construction are heat, scarify, compact, apply oil additive and overlay. Usually there is a delay between application of the recycling agent and the overlay. A roller should follow immediately behind the scarifying machine so that the mix is compacted at an elevated temperature. The recycling oil is than applied, usually at the end of the working day, insuring a continuous uniform application.

After the pretreatment is completed, the asphalt laydown operation proceeds at a uniform rate of speed, coordinated with the arrival of trucks to the spreader. This is most evenly matched with the plant capacity which leads to a higher quality finished surface at a reduced paving cost.

If the street is open to traffic for a prolonged period before a cover is installed, some caution should be exerted to prevent high speed traffic degradation of the surface. This can be done by signs or a light application of emulsified asphalt on the surface to tighten up the aggregate and provide an armour until the resurfacing or seal treatment is scheduled.

Process Improvements

1. Contaminants or multiple chip seals should be cold planed in advance to allow proper heat transfer to underlying material.

2. Multimple machines raise temperature in even gradients without damaging asphalt binders.

3. Mechanical screeding levels and redistributes material from deep scarifying.

4. Rolling densified recycled mix while temperature remains elevated.

5. Recycling agents available in varieties to suite different pavement conditions are applied after compaction.

6. Two stage construction permits lower cost of installing thin overlays.

A project will usually be more efficiently accomplished using stage construction for the following reasons.

> The two stage operation is more economical for each operation and will actually provide a more uniform and better product in the final analysis. In post job samples of two stage and train operations, there is no visible lack of bond when using the two step operation.
>
> The inspector viewing surface recycling can measure scarification depth and control the rate of application of recycling agent. He can later observe the paving operation without dividing his time between the two functions. Density requirements specified by most agencies can be more easily obtained in the two stage operation. A rubber tired compactor is preferred, but a steel roller may be utilized to densify the remixed surface and provide compaction immediately following heater scarifying.
>
> Should the condition of the existing pavement warrant a heavy application rate of recycling agent, a delay of several days may be necessary for the agent to be absorbed into the pavement so that bleeding through the overlay is avoided. A uniform application eliminates the distributor marks caused by overspray and laps.

It is my belief by the use of seal coats and thin asphalt overlays to cover the streets that need improved riding qualities the waterproof flexible structures can be extended. Surface recycling offers engineers an ideal way of preparing and rehabiliting the pavement section to bring it to the conditions where these thin overlays can be installed to add life. Many Western cities have pioneered the development of higher quality surface recycling to virtually eliminate reflective cracking through thin asphalt overlays and save as much as 25 to 30 percent of the cost of new material at today's prices. As the cost of asphalt cement escalates and its availability diminishes, the use of surface recycling must be considered in more and more instances to rehabilitate existing streets.

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2. Interim Guidelines for Recycling Pavement Materials, NCHRP Report No. 224, Transportation Research Board, 1980.
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4. R.J. Peters, Surface Recycling - Quality Control, Asphalt Recycling and Reclaiming Association, Palm Springs, California, March 1980.
5. Asphalt Institute MISC 77-3, 1977, Surface Recycling of Asphalt Pavements by the Heater Overlay Process.
6. D.D. Davidson, William Canessa and S.J. Escobar, Practical Aspects of Reconstituting Deteriorated Bituminous Pavements, 1979, American Society of Testing Materials.
7. R.F. Coons and Paul H. Wright, An Investigation of the Hardening of Asphalt Recovered from Pavement of Various Ages, Proceedings of the Association of Asphalt Paving Technologists, Volume 37, 1978, Page 510.
8. William Canessa, Reclamite's Function with the Heater Scarifyer, Fifth Annual Texas Public Works Short Course, Texas A&M, College Station, Texas, February 23-25, 1976.

Appendix A - Guide Specification

The work shall be accomplished by heating, scarifying, releveling, compacting and applying a recycling agent to the existing asphalt surface.

Equipment

1. The equipment used to heat and scarify asphalt surface shall be fueled by liquified petroleum gas. It shall fully meet the standards of the State and Local Bureau of Air Pollution Control. The combustion chamber shall be insulated, rear wheel positioned and equipped with burners rated at a minimum of 15,000,000 BTU's per hour. The machine shall be equipped with two rows of spring-equalized scarifier leveling rakes, removable heard-faced teeth incorporating an automatic release for manhole and valve protection. A competent operating crew, including a service vehicle shall be provided.

2. The equipment used to distribute and level the scarified material shall be an approved paving machine equipped with an operating vibratory or oscillating heated screed. A two man operating crew shall be provided.

3. One pneumatic-tired roller with operator shall be furnished to compact the scarified material. The contractor alternately may furnish another type compactor if approved by the engineer.

4. One asphalt, cab-controlled, liquid spreader with operator shall be furnished to distribute the asphalt rejuvenating agent.

Construction Details

Prior to commencing surface recycling, the pavement shall be cleaned of all extraneous material. Power brooming may be supplemented by hand brooming until all deleterious material has been removed.

A minimum of two heater units will be utilized in tandem so that the heat emitted and the rate of travel will achieve specified requirements. The number of additional heater units shall be determined by the contractor; however, only the scarifier rakes on the final heater unit of the series shall scarify. A minimum production of 15,000 square yards per day shall be required.

The existing asphalt surface shall be heated from 6 to 12 inches wider than the width to be processed. The temperature of the scarified material shall be between 200 and 300°F when measured behind the scarifier.

The weight of existing asphalt surface has been estimated to be approximately 144 pounds per cubic foot. On this basis, a minimum of nine pounds per square foot of existing surface shall be scarified to obtain a depth of between 3/4 and 1 inch. If tests indicate that the material weighs either less than 137 or more than 151 pounds per cubic foot, the weight per square foot requirement will be adjusted accordingly by the engineer.

Scarification will be deemed acceptable when the moving average of three consecutive random weight tests per hour indicates that the required depth has been scarified. The weight of the existing asphalt surface will be determined in accordance with the requirements of AASHTO T-166 from scarified material compacted in accordance with requirements of AASHTO T-245, with the exception that the compaction temperature shall be 270°±F.

The scarified material shall be distributed and leveled only the width processed and be rolled immediately while it possesses sufficient heat to be properly compacted. Following compaction, the asphalt recycling agent shall be applied undiluted to the retreated surface. The rate of application shall be determined by the enigneer based on laboratory tests of the material and analysis of the effect on the embrittled asphalt binder.

In addition to the applicable specification covered by R.A. Jimenez (1), the following items are of special interest for urban work.

Protection of Existing Improvements

Since high temperatures are required in the surface recycling operation, the Contractor shall exercise care against possible injury or damage to existing improvements. The Contractor shall protect all existing curbs, gutters, trees, shrubbery and other improvements from damage. The smaller parkway trees shall be protected by shields and overhanging trees may be sprayed with water to inhibit damage. No machine with an open flame exhaust will be permitted. Existing improvements damaged by the Contractor shall be repaired or replaced to the satisfaction of the City Engineer at no cost to the City.

Smog Control

The Contractor shall minimize the escaping of solids into the air by either the machine or burning of pavement during the heater-remix operation. The machine shall be operated under a permit of the local Air Pollution Control District and shall not be in violation of Rule 1120, South Coast Air Quality Management District requirement. In the event that a smoke problem develops and becomes excessive, it may be necessary to remove the contaminant by cold planing to reduce the problem. No additional compensation will be allowed for any necessary steps required to reduce emissions.

Testing and Control

The Contractor shall furnish the services of a registered professional engineer and laboratory specializing in asphalt technology. Abson recovery tests shall be made on representative cores prior to construction to obtain asphalt penetration (ASTM D-5) and to determine results of treating binder with variable types of additive. No work shall be undertaken until the laboratory report has been approved by the Engineer. At an appropriate period following construction, cores shall be taken from the streets and a report made to the Engineer indicating changes in asphalt penetration and ductility obtained by recycling. The cost of testing and preparation of reports shall be included in the cost per square yard for heating and remixing surface. The number of cores required shall not exceed 1 per 10,000 square yards of treated pavement.

Measurement and Pavement

Cost of pretreatment, including cleaning and heater-remixing, but excluding recycling agent, shall be paid for in square yards of surface area covered regardless of the number of operations involved to obtain a satisfactory job in the opinion of the Engineer.

The asphalt recycling agent, paid for by weight, shall be weighed on sealed scales regularly inspected by State Bureau of Weights and Measures, or may be measured in some other approved manner. A load slip shall be furnished for each vehicle weighed and slip shall be delivered to the Engineer at point of delivery of material. Asphalt concrete overlay required shall not be paid for under this section.

Appendix B

Rule 1120 - Asphalt Pavement Heaters

A person shall not operate an asphalt pavement surface heater or an asphalt heater-remixer for the purpose of maintaining, reconditioning, reconstructing or removing asphalt pavement unless all of the following requirements are met:

1. Black or gray smoke emission of more than 60 consecutive seconds duration shall not be discharged to the atmosphere and in aggregate, black or gray smoke emissions shall not exceed a total of three minutes in any one hour of heater operation. For the purpose of this rule, black or gray smoke is to be viewed by an observer at the point of greatest opacity.

2. Visible emissions of more than 40% opacity, other than black or gray smoke, shall not be discharged to the atmosphere for a period of periods totalling more than three minutes in any one hour. For the purpose of this rule, visible emissions are to be viewed by an observer at a point no lower than 36 inches above the pavement.

3. All units of equipment are fired with gaseous fuels that do not contain in excess of 80 ppm by volume of sulfur compounds calculated as H_2S, or with diesel fuels that do not contain more sulfur than specified by the California Air Resources Board.

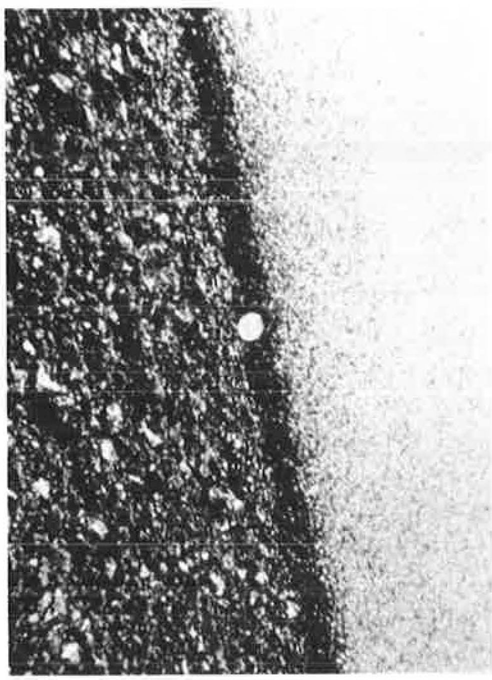
4. Grease, crack pouring materials or oily substances that burn or produce smoke are removed by mechanical grinding, by cold planing or by other mechanical means prior to the use of the heating equipment on the contaiminate area.

5. Asphalt pavement at the work site is cleared of paper, wood, vegetation and other combustible refuse prior to operation of the heating equipment.

6. The Executive Officer is notified of an operation using pavement heaters within 10 days after a contract is signed authorizing such work and again, at least 24 hours before an operation starts. Each notification shall describe the location, estimated starting time and an estimate of the time to complete the work.

7. The equipment is operated only during days on which open burning is allowed. However, an operation that begins on a day when open buring is allowed, may be continued on successive days whether open burning is allowed or not allowed. Information concerning whether a proposed operating day meets the criteria specified in this subparagraph (g) may be obtained from the Executive Officer or his authorized representative.

LARGE SHRINKAGE CRACKS FROM EMBRITTLED ASPHALT, ACCUMULATED TRANSMISSION OIL DRIPPINGS, AND WATER DETERIORATION AT GUTTER

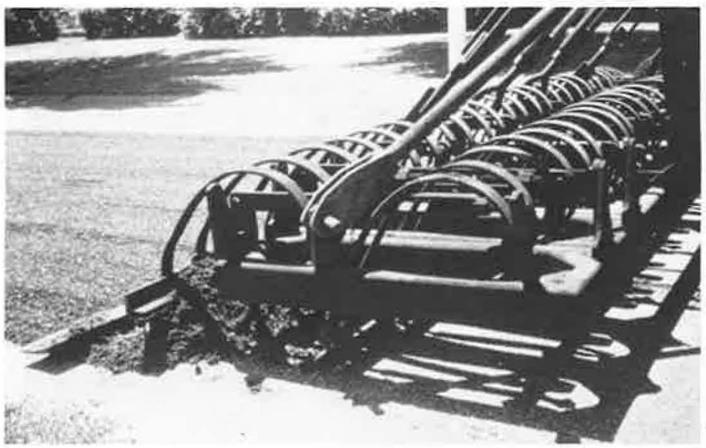


LOOSE REMIXED PAVEMENT ON LEFT THIN 10 LB/SQ. FT. OVERLAY AT RIGHT

1963 PHOTO OF FATIGUED SECTION (2" AC OVER 8" CRB) WITH RECYCLED SURFACE AND 1" AC BLANKET AT RIGHT, OVERLAY IS STILL IN SERVICE TODAY WITHOUT MAINTENANCE

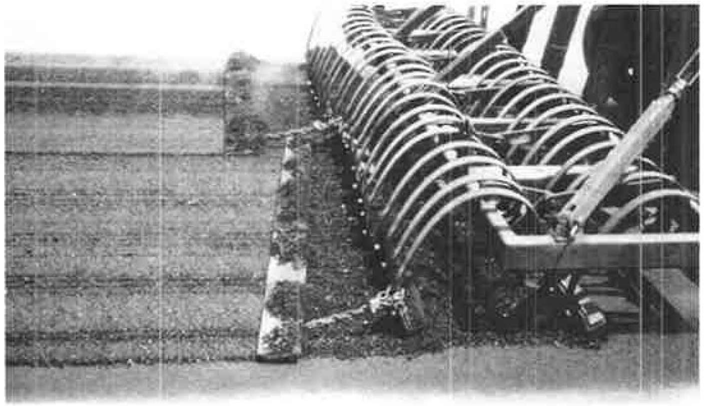
HEATER SCARIFYER, RAKERS AND ROLLER FORM CITY MAINTENANCE PROGRAM

RECYCLING OIL ADDED TO COMPACTED PAVEMENT



CLOSEUP OF RAKES SHOWING LOOSENED MATERIAL AND STRIKE-OFF

SECOND SLURRY COAT APPLIED OVER PRETREATMENT TO FINISH THIS PROJECT



DEEP SCARIFYING LEVELING WITH SIMPLE BLADE DRAG

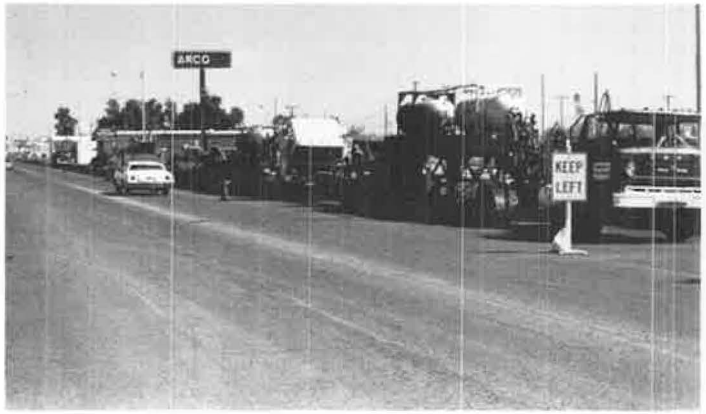
CHIP SEAL WITH UNSEALED CONTROL SECTION IN FOREGROUND

COMPACTED SURFACE AFTER RECLAMITE APPLICATION

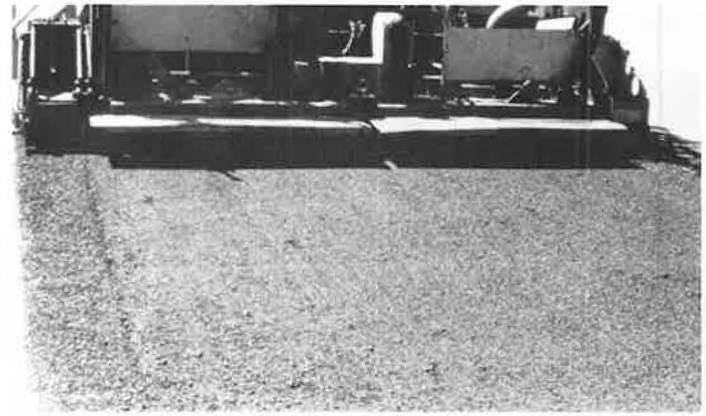
CLOSEUP OF 3/8" MAXIMUM CHIP TREATMENT ON RECYCLED PAVEMENT

EXTRA LONG 30' COMBUSTION CHAMBER FOR SURFACE RECYCLING MATERIAL, COURTESY ASPHALT EQUIPMENT, INC.

CLOSEUP OF RAKE PENETRATION FROM H.D. SCARIFYER ASSEMBLY PRODUCING 1" SURFACE RECYCLING - NOTE SHRINKAGE CRACK AT RIGHT

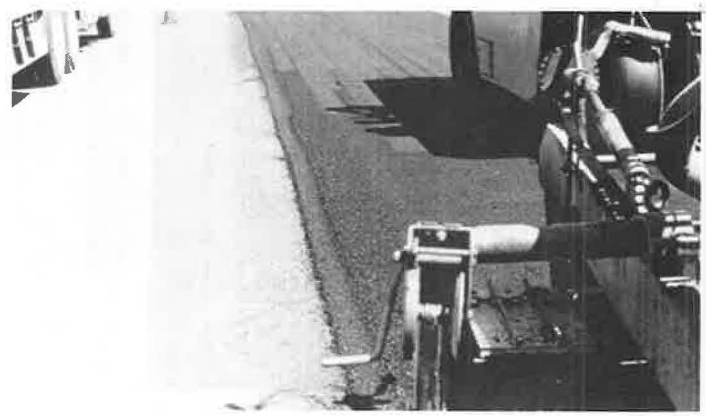


TWO STAGE RECYCLING IN COOLIDGE, ARIZONA WITH 2 HEATERS - NOTE CLEANLINESS OF OPERATION



SCREEDED MATERIAL 9 LB/SQ. FT. AT 270^{o}F PRIOR TO COMPACTION

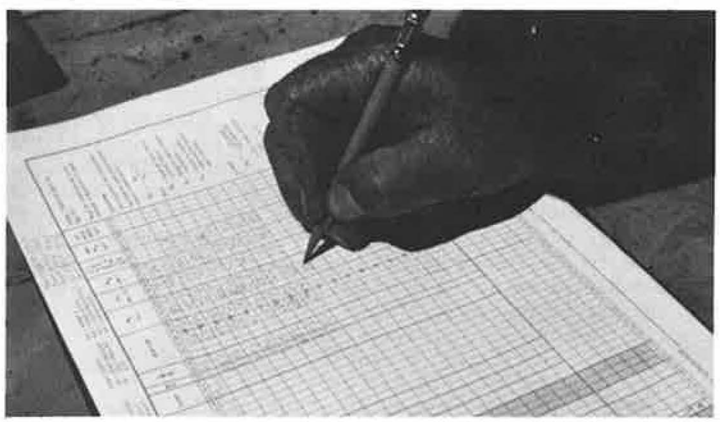
SCREED, RUBBER TIRED COMPACTOR AND OIL SPREADING TRUCK



RUBBER TIRED COMPACTOR FOLLOWS CLOSE TO SCREED

INSPECTOR MEASURES TEMPERATURE AND TAKES SAMPLE
OF RECYCLED MATERIAL FRONT OF SCREED

CLOSEUP OF MATERIAL AND GRADUATED TEST RING



SAMPLE WEIGHT IS NOTED AND MOVING AVERAGE OF
3 PER HOUR DETERMINES COMPLIANCE

RURAL SURFACE RECYCLING

Rowan J. Peters, Arizona Department of Transportation

Federal, state and local agencies are currently faced with a number of very critical problems which include the reduction in available funds due to inflation, a declining tax base, and declining revenue from taxes on fuel. A possible answer to these current problems is the serious consideration to re-use existing in-place materials be recycling for construction and maintenance needs. By recycling we conserve energy and materials (aggregates, binders, guardrail etc.) and are able to preserve the pavement geometrics and environment. The Arizona Highway Division began using the surface recycling-Reclamite rejuvenating agent process about 12 years ago. Before that time it was using the rejuvenating agent as a surface treatment only to routinely maintain its roads. However, there were limitations to its use since in many instances the pavement surfaces were far too deteriorated for this type of treatment to be effective. The advent of the surface recycling program, in which heater scarification of the old pavement surface and Reclamite rejuvenation treatments are combined, overcame these deficiencies. Control techniques devised by the Highway Division of the Arizona Department of Transportation have played an important part in the success of a continuing program to repair deteriorated asphalt pavements by surface recycling methods. The effectiveness of the quality control practies, which deal primarily with close control of proper scarification depth of the old pavement, has made it possible for the division to gain optimum results from surface recycling which not only produces durable asphalt road surfaces but also helps conserve resources and energy.

Control techniques devised by the Highway Division of the Arizona Department of Transportation have played an important part in the success of a continuing program to repair deteriorated asphalt pavements by surface recycling methods. The effectiveness of the quality control practices, which deal primarily with close control of proper scarification depth of the old pavement, has made it possible for the division to gain optimum results from surface recycling which not only produces durable asphalt road surfaces but also helps conserve resources and energy.

The Arizona Highway Division began using the surface recycling-Reclamite rejuvenating agent process about 12 years ago(1, 2). Before that time it was using the rejuvenating agent as a surface treatment only to routinely maintain its roads. However, there were limitations to its use since in many instances the pavement surfaces were far too deteriorated for this type of treatment to be effective. The advent of the surface recycling program, in which heater scarification of the old pavement surface and Reclamite rejuvenation treatments are combined, overcame these deficiencies.

What is more important about the ability of the process to reduce asphalt consumption is the conservation of resources that are dwindling. This is a very practical consideration. The energy required for making new asphalt pavement and the crude oil-based ingredients of asphalt cement itself are becoming more costly and scarce.

What is presently called asphalt pavement surface recycling in today's environmentally conscious world would have been described in the past by other terms; e.g., heater-scarification or heater remixing, etc. Aside from terminology, the process has always been a multi-step procedure of heating the existing surface, scarifying, remixing, compacting and adding a rejuvenating agent.

Design Objective

The prime purpose behind the use of the strategy of surface recycling is to develop a low modulus layer of bituminous material with the flexibility to retard the propogation of cracks. In effect, the attempt is to break the cracking pattern of the existing pavement surface and form a restructured layer capable of disseminating the stresses that develop in pavements. The restructured layer is only effective if it has been adequately formed and its ultimate performance is dependent upon a number of parameters such as environment, pavement structure and construction.

To this point there has been little consideration given to assigning any structural value to the recycled surface layer. As our experience increases and we improve our ability to achieve the desired objective including the increased depths of scarification that we can begin to quantify the "structural" improvements and perhaps reduce overlay thicknesses accordingly when they are employed with the surface recycling strategy.

When we consider the fact that we may never again have the opportunity to rejuvenate this particular layer of the pavement structure due to subsequent overlays, seal coats etc, it becomes that much more important that due consideration be given all elements involved. Proper rejuvenation requires an adequate addition of recycling agents to the recycled surface. This quantity of recycling agents should be determined by laboratory testing on cores taken from the surface to be recycled. Assuming a scarification depth of 2cm (3/4 inch), this top 2cm (3/4 inch) of the cores is removed for testing. The asphalt recovered from the 2cm (3/4 inch) slice is tested for absolute viscosity at 60°C (140°F). The quantity of recycling agent required to return the asphalt to a viscosity level which would be comparable to a new asphaltic concrete is determined by trial additions of the agent with the recovered asphalt.

The quantity of the recycling agent specified is dependent upon the complete interaction with the asphalt throughout the 2cm (3/4 inch) depth. Realistically the success of this interaction is dependent upon many factors with the prime factor being our ability to achieve the specified amount of scarified material. The quantity of the rejuvenating agent actually used is also dependent upon the ability of the recycled surface to "accept" the specified fog application of recycling agent. A complete rejuvenating interaction may require 1.13 liter per square meter (0.25 gallon per square yard) of the agent; however, the condition of the recycled surface may be such that a greater or lesser quantity is appropriate. It is suggested that specimens should be formed that approximate the compacted scarified material and varying application rates tested for completeness of penetration or potential flushing problems.

It is further suggested that variations in roadway surfacing be handled separately. For instance, maintenance seal areas that are usually higher in asphalt quantities may not be able to handle the same quantity of rejuvenating agents. The key point is that adjustments to the design must be considered throughout the project as varying conditions arise. We should not expect to set application rates at the beginning of a project and not expect to have need to alter them throughout the course of the project.

Design Decision Criteria

The question is often asked as to when one should consider the use of the surface-recycling strategy. Many times, without firm design criteria at hand, this decision is made based on ones personal experience and intuition. Besides the advantages of rehealing and restoring the surface, we mainly look at the use of the strategy for inhibiting reflective cracking.

In order to determine when to employ the strategy, utilization of a cracking index photo representation is relied upon(3). The cracking index represents the percentage of cracks of a sample of 1000 square feet of roadway. Currently we consider surface recycling a pavement that has greater than 10% cracking. The difficult decision is to determine the point when we begin to more seriously consider hot-mix recycling or in-place cold recycling. At this point, it appears that above 40% cracking we should begin to look at those alternate strategies.

Figure 1. Approximately 10% Cracks

Figure 2. Approximately 35% Cracks

Construction Quality Control

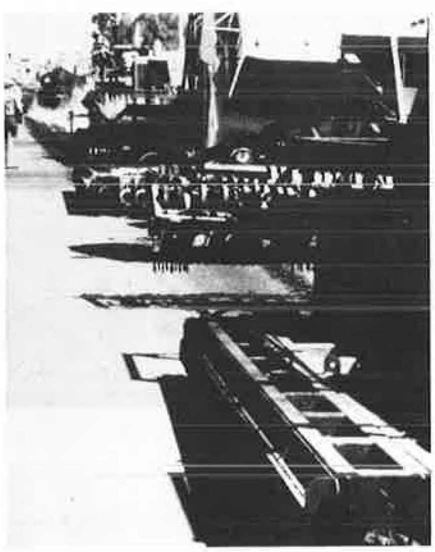
As mentioned previously, the most important aspect of surface recycling needed to produce a satisfactory product is to achieve the design depths of scarification and to add the proper amount of the recycling agent to this total depth. To accomplish this end it is important to exert control over a number of construction details such as:

1. Weather Consideration. It has been found necessary to control the time of year the surface recycling should be done depending on project elevation. The work is generally restricted to the dates shown; however, the beginning date may be moved ahead and the ending date may be extended if, in the opinion of the engineer, weather conditions, surface temperatures and other factors will not have an adverse effect upon the work. At any time the engineer may require that the work cease or that the workday be reduced in the event that weather or other conditions will have an adverse effect upon the product.

Average Elevation of Project, Feet	Beginning and Ending Dates
0 - 3499	February 15 - December 15
3500 - 4999	April 1 - October 31
5000 and over	May 1 - September 30

2. Heating Units. The number of heater units utilized is determined by the contractor; however, if all heater units are equipped with scarifiers, only the scarifier on the last heater unit of the series is allowed to be used for scarification. Multiple heater units are utilized in tandem such that the heat emitted and the rate of travel will achieve the specified depth requirement.

Figure 3. Operating Train - Two Heating Units Followed By a Heating and Scarifying Unit



The existing bituminous surface is heated not less than 15cm (6 inches) nor more than 30.5cm (12 inches) wider than the width of the material to be scarified. The temperature of the scarified material measured immediately behind the scarifier should be not less than 93.3°C (200°F) nor more than 149°C (300°F).

3. Depth of Scarification. Here is where the new quality control practices have proved so valuable(4). One of the keys to successful surface recycling is following the specification for scarification depth, which is critical for achieving proper penetration of the rejuvenating agent. Optimum scarification depth is considered to be 3.3 cm (1 1/4 inches) of loose or 2cm (3/4 inch) of compacted scarified asphalt mix depending upon specific project conditions. Depth probes have not been very satisfactory as a means of determining whether the proper scarification depth is being maintained. Instead the division has devised a new positive method.

Based on a specific weight of 2306Kg per cubic centimeter (144 pounds per cubic foot), the weight of one square foot of scarified mix at the specified depth is 4.09Kg (9 pounds). In order to confirm that specifications are being met, a state inspector periodically monitors weight on-site be setting known-diameter rings into the asphalt surface after the scarifier and ahead of the roller operations. He scoops the loose contents out completely and weighs them to ascertain that they conform to the 4.09Kg (9 pounds) per square foot criterion. Rings are set out at 20-minute intervals and placed in a continous pattern from one side of the road to the other and then to the center. If samples from three successive rings do not weigh out correctly, operations are halted and the speed adjusted until proper depth scarification is achieved.

These specifications and the quality control measures used to enforce them are strict, but they do not help attract the qualified contractors who can provide the kind of results needed for this program.

Note: The complete specification for the "Recycling of Existing Bituminous Surface" can be obtained from the author or is available on a report given to the Asphalt Recycling & Reclaiming Association(5).

The Highway Division is committed to the surface recycling concept because of the very real advantages that can be gained from its use. One is the increase in the quality of new asphalt pavement surfaces. When using a conventional 5.3cm (2 inch) asphalt pavement overlay - an approach employed for many years and still used in many areas - the new surface inherits many of the defects of the old one. Since the overlay is placed on top of a surface containing cracks and other irregularities, overall stability of the new surface is reduced and the need for future maintenance attention is increased.

4. Leveling and Recycling Agent Fog. The width of the bituminous surface processed is limited to the original width of the material scarified. The bituminous surface is compacted immediately after it has been distributed and leveled and while it is still hot. Within 30 minutes after compaction the Emulsified Recycling Agent should be applied. No material to which Emulsified Recycling Agent has been applied can be reheated and rescarified. If the engineer determines that excessive ravelling is or has occurred, he may direct the contractor to apply an Emulsified Asphalt.

Future Needs

As has been said before "nothing is as constant as change itself" and this is so true in the evolution of surface recycling specifications. There is little reason to believe that we will not go through additional alterations as processes and needs dictate change.

It has been repeated on numerous occasions that the addition of a recycling agent is very much a part of the surface recycling strategy. If there is a weakness still remaining in the strategy, it would be the need for a field control method for determining application rates for the recycling agent during construction. As we control depth of scarification so must we be able to adjust application rates of the recycling agent for varying field conditions.

Another need might be to insure that we have optimized the depth achievable or can equipment development obtain additional recycled depth? Greater depths may preclude the needs for cold recycling on some occasions. The basic need being the determination of where and when to surface recycle as compared to hot and cold recycling. With time developments will address these needs and an improved surface recycling strategy should evolve.

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STATE-OF-THE-ART COLD RECYCLING

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Cold recycling is desirable. Not much equipment is required and processing in-place enables structural and material problems to be corrected quickly without much disruption to traffic. Where an existing asphalt concrete course is pulverized and mixed together with the existing aggregate base, the residual asphalt acts as an excellent binder to help make the recycled base waterproof and less frost susceptible. The addition of new binder or chemical stabilizer may further upgrade the recycled base by reducing swell potential where active clays are present in the base, by reducing freeze-thaw potential, by waterproofing the base aggregate and/or by increasing the load-carrying capacity of the pavement structure. With an increased load-carrying capacity in the base course, the pavement structure may be constructed thinner. The ultimate decision as to application of in-place recycling is based on a total evaluation considering user utility, structural requirements, energy expenditures, and cost.

Rehabilitation and maintenance of our present transportation system is costly, time consuming and material intensive. In the last five years reuse or recycling of existing pavement materials has emerged as a viable rehabilitation and maintenance alternative as it offers several advantages over the use of conventional materials and techniques (Figure 1). Among the major benefits are lower costs, conservation of aggregates, binders and energy, and preservation of the environment and existing highway geometrics.

Since the benefits of recycling appear promising from a wide variety of viewpoints a number of agencies including the National Cooperative Highway Research Program (NCHRP) have sponsored research (1, 2). NCHRP Synthesis 54, "Recycling Materials for Highways" was the first comprehensive summary of recycling information (1). Federal Highway Administration sponsored programs include: Demonstration Project No. 39, "Recycling Asphalt Pavement" (3, 4); Demonstration Project No. 47, "Recycling Portland Cement Concrete Pavement" (5); National Experimental and Evaluation Program (NEEP) Project No. 22 (6); Implementation Package 75-5 (7); Office of Research studies on "Softening or Rejuvenating Agents for Recycled Bituminous Binders," "Tests for Efficiency of Mixing Recycling Asphalt Pavements," Data Bank for Recycled Bituminous Concrete Pavement" and "Materials Characterization of Recycled Bituminous Paving Mixtures" and HPR and special state studies (8, 9). Other government sponsored studies have been performed by the Corps of Engineers (10) and the Navy (11).

Associations and Institutes that have contributed to the collection and distribution of recycling information include the American Concrete Paving Association, Asphalt Emulsion Manufacturers Association, Asphalt Reclaiming and Recylcing Association, The Asphalt Institute (12), National Asphalt Pavement Association (13, 14), Portland Cement Association (15) and West Coast User-Producer Group on Asphalt Specifications (16). In addition conference sessions and symposiums have been held on pavement recycling at the Transportation Research Board, American Society for Testing and Materials (17) and Association of Asphalt Paving Technologists meetings.

Definitions

The term pavement recycling has not been formally defined. However, most individuals concerned with roadway rehabilitation use the term to indicate "the reuse (usually after some processing) of a material that has already served its first-intended purpose in a roadway" (18).

Definitions for 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 (19), Asphalt Recycling and Reclaiming Association (20), National Cooperative Highway Research Program (1, 2), U. S. Army Engineers Waterway Experiment Station (10), and Navy Civil Engineering Laboratory (11). Although formal definitions for recycling categories have not been developed those advanced by a joint National Asphalt Pavement Association, The Asphalt Institute and Federal Highway Administration committees are the most widely accepted and are given below:

Asphalt-Pavement Surface Recycling. One of several methods where the surface of an existing asphalt pavement is planed, milled, or heated in-place. In the latter case, the pavement may be scarified, remixed, relaid, and rolled. Additionally, asphalts, softening agents, minimal amounts of new asphalt hot-mix, aggregates, or combinations of these may be added to obtain desirable mixture and surface characteristics. The finished product may be used as the final surface or may, in some instances, be overlayed with an asphalt surface course.

Cold-Mix Asphalt Pavement Recycling. One of several methods where the entire existing pavement structure including, in some cases, the underlying untreated base material, is processed in-place or removed and processed at a central plant. The materials are mixed cold and can be reused as an aggregate base, or asphalt and/or other materials can be added during mixing to provide a higher strength base. This process requires that an asphalt surface course or surface seal coat be used.

Hot-Mix Asphalt Pavement Recycling. One of several methods where the major portion of the existing pavement structure including, in some cases, the underlying untreated base material, is removed, sized, and mixed hot with added asphalt cement at a central plant. The process may also include the addition of new aggregate and/or a softening agent. The finished product is a hot-mix asphalt base, binder, or surface course.

Portland-Cement Concrete Pavement Recycling. A process by which an existing portland cement concrete pavement is processed into aggregate and sand sizes, then used in place of, or in some instances with additions of conventional aggregates and sand, into a new mix and placed as a new portland cement concrete pavement. This process is a phase of the econo-crete concept in that the broken concrete is considered to be a local aggregate.

This conference is directed towards asphalt pavement recycling while this paper presents the state-of-the-art relative to cold-mix asphalt pavement recycling.

Cold-Mix Asphalt Pavement Recycling. As indicated by the definition cold-mix recycling involves the reuse of existing surface, base, subbase and/or subgrade materials. The material can be reprocessed in-place or it can be removed and processed in a central plant without the addition of heat. New binders such as lime, portland cement and bituminous materials can be used in the recycling process. After the roadway has been pulverized, mixed and placed, it will normally require a new wearing surface such as a surface treatment or asphalt concrete.

Cold recycling is an attractive pavement rehabilitation alternative. Equipment required for cold recycling is of basically a conventional nature, much the same as used in conventional soil or aggregate stabilization procedures. Thus, the equipment is readily available. The major advantages and disadvantes of in-place cold recycling operations are compared with surface and hot recycling operations on Table 1.

Advantages. Major advantages of cold recycling operations include:

1. Ability to achieve significant pavement structural improvements,
2. All types and degrees of pavement distress can be treated,
3. Reflection cracking can be eliminated if the depth of pulverization and reprocessing is adequate,
4. Frost susceptibility of subgrade and subbase soils can be improved by use of the process,
5. The pavement ride quality can be improved,
6. Skid resistance can be improved (depending upon type of surface placed on cold recycled section) and
7. Hauling costs can be minimized if processing takes place on grade.

Disadvantages. Cold recycling operations have several disadvantages when compared to other pavement rehabilitation operations. The disadvantages include:

1. Pulverization equipment is often in need of frequent repair and thus production can be low,
2. Traffic disruption can be greater than some other types of rehabilitation activities,
3. Portland cement concrete pavements cannot be recycled in-place,
4. Curing is normally required for strength gain,
5. Strength gain and construction is susceptible to climatic conditions including temperature and moisture and
6. Quality control for in-place operations is not as good as central plant operations.

Future of Cold-Mix Recycling. During the last 10 years highway construction, rehabilitation and maintenance costs have increased by a factor of nearly three. Funding at the federal, state and local level during this same time period has increased slightly. Therefore, it is critical that each available dollar be expended in the most cost-effective manner.

This funding situation which is expected to continue through the next few years is forcing governmental agencies to expend the available funds for roadways on rehabilitation and maintenance operations. Since recycling is a cost-effective rehabilitation and maintenance alternative, the future for all forms of pavement recycling is encouraging. Recycling will capture an increasing proportion of the estimated 34 billion dollars expended on highways in the United States.

Cold recycling will capture a significant share of those funds expended on recycling. The advantages listed above make cold recycling a prime candidate for roadways without surfaces and roadways with this asphalt bound wearing surfaces. Table 2 indicates that 48 percent of our nation's 3,884,761 miles of road are non-hard surfaced (21). An additional 28 percent of the roads are surfaced with thin layers of bituminous materials. Since several surface recycling operations can not be used on thin surfaced and non-hard surfaced pavements and since large scale hot-mix recycling operations may not be economical on thin surfaced and non-hard surfaced pavements, "the future for cold recycling is very promising."

Methods, Equipment and Quality Control

In-place recycling of old asphalt 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 are among the more important recent refinements of in-place recycling.

The various alternatives for in-place pavement recycling with no additional heat are shown in Figure 2. Stabilizers such as lime, cement, asphalt, and other chemicals have been used in these processes. Use of cement as stabilizers for recycled bases and surfaces dates to 1942 (22). Use of asphalt with recycled material probably dates to the early 1940's, although the most recent work indicates 1966 (23). 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 and surfaces without the addition of a stabilizer.

Methods (In-Place). The basic sequence of operations for in-place surface and base recycling is shown in Figure 2. As noted the separation of techniques is based on the thicknesses of the surface course (stabilized material). When the thickness of the stabilized layer is approximately 2 inches or less, pulverization can be performed without a ripping and breaking operation. Pulverization of stabilized materials at depths greater than 2 inches can be performed economically with special equipment. Cold milling machines and specially altered soil stabilization equipment can pulverize to depths of about 5 to 7 inches economically.

The second separation of in-place recycling techniques is based on the use of a stabilizing agent. The stabilizer is most often an emulsified asphalt, lime, cement or fly ash in combination with lime or cement.

Experimental models of recently designed machines now make it possible to pulverize, add and mix a stabilizer and grade the surface in a single pass - single machine operation. The appearance of these types of machines in everyday practice will reduce costs and traffic disruption.

The literature indicates that a number of construction sequences have been utilized to complete the essential steps of pulverization, adding and mixing stabilizers and grading and compacting the recycled material. Figures 3 and 4 present typical operations. Figure 3 shows the recycling operation using no additional stabilizer but adding existing base and/or new aggregate to the processed bituminous bound material. Figure 4 shows the recycling operation using a stabilizer, the existing base and/or new aggregate. Note that a recycling agent or modifier has been added to the pulverized recycled bituminous bound material prior to the addition of the existing and/or new base.

With the advent of new equipment it is not unusual to pulverize with one machine in one pass and add stabilizer and mix with a second machine. Whatever the sequence of operation used in cold recycling the major operations consist of

1. Pulverization,
2. Adding and mixing stabilizers or water,
3. Fine grading,
4. Compaction and
5. Curing.

Equipment associated with these operations will be briefly discussed in another section of the report.

Methods (Central Plant). Central plant cold recycling operations are very similar to those performed in-place. Pulverization of the recycled material can take place 1) on grade as part of the pavement removal operation, 2) on grade after initial ripping and breaking or 3) at the site of the central plant after initial ripping and breaking has taken place on-grade. Typical cold-central plant operations are shown in Figure 5.

Central plant mixing operations afford the best opportunity to produce uniform stabilized materials and can achieve close to 100 percent mixing efficiency as measured by the strength of the treated soil measured after field versus laboratory mixing. Of the two major types of central plants, the batch plant will normally have better uniformity and control than the continuous plant. However, continuous plants are used more often than batch type plants due to their high production capabilities.

Equipment. The types of equipment used for in-place recycling are very similar to those used for on-grade stabilization with lime, cement or asphalt. Generally, the only specialized equipment is that used to properly size bound materials prior to stabilization.

Typical soil stabilization construction equipment is identified in Figure 6 and identified with type of stabilizer in Table 3 (24). Excellent general summaries of soil stabilization construction equipment and construction operations can be found in References 25 and 26 for lime stabilization operations, References 27 and 28 for lime-fly ash, Reference 29 for cement stabilization and Reference 30 for asphalt stabilization (24).

As indicated above pulverization and pavement removal equipment developments have greatly contributed to the economic viability of cold recycling operations. John Wood's paper "Equipment for Cold Recycling" (31) presented at this conference summarizes equipment developments unique to cold recycling. A brief summary will be presented here for completeness.

Categorization of pavement removal and pulverization equipment commonly associated with cold recycling operations is shown in Figure 7 (1). It should be noted that the majority of this equipment is associated with either surface recycling or soil stabilization operations.

Heater-Planers and Heater-Scarifiers. Heater-planer and heater scarification is an outgrowth of equipment developed by Gibbons and Reed Contractors of Salt Lake City in the 1930's (32). Advancements in equipment technology have been made and now in excess of 10 companies have developed this type of equipment (1). Bituminous bound materials removed from heater-planer and heater-scarification equipment have been used without the addition of stabilizers on shoulder, as pavement base courses and for maintenance patching. This type of equipment is normally not used as a pavement removal process for cold recycling operations.

Hot-Millers. Hot-milling has not been used extensively in the United States. The process is limited to asphalt-surfaced roadways and has not been used extensively as a pavement removal process for cold recycling operations. Wirtgen and the Millars Company manufacture equipment.

Cold-Planing. Motorgraders have been used to plane asphalt pavements in the summer months. These materials have been reused to a limited extent.

A pavement planer capable of being used for cold recycling operations is under development by Envirodyne in Reno, Nevada (1). This planer removes pavement by use of the vibratory beam concept.

Cold-Milling. Cold-milling equipment has been used extensively for pavement removal and pulverization. Much of this equipment has been developed since 1973. Most of the larger units were not developed until after 1976. CMI, Barber-Greene and BARCO presently manufacture larger machines while BJD, Cutler, Galion, Payne, Reconeco and Sakai are some of the manufactures of smaller cold planers. One company is developing a machine capable of pavement removal, pulverization, adding stabilizer, mixing and laydown in a single pass.

Pavement Rippers. Typically pavement ripping is performed by crawler tractors pulling one to two ripper teeth. Large scale trenching tools have been used for pavement loading on at least one job in Nevada.

Traveling Hammer Mills. Traveling hammer mills have been developed and used for cold recycling operations by Pettibone and Independent Construction Company (1). This equipment is often used to pulverize the ripped and windrowed pavement.

Soil Stabilization Equipment. Some contractors have improved existing soil stabilization equipment with or without the cooperation of soil stabilization mixing equipment manufacturers. This equipment is capable of pavement removal and pulverization in a single pass. Pulverization can be obtained to depths of 5 inches in stabilized materials. Old P&H pulver-mixers, Koehring and Pettibone equipment has been upgraded by contractors and equipment manufacturers. Considerable detail on these commonly used cold recycling equipment items can be found in John Wood's paper.

Quality Control

The objective in cold recycling is to obtain a thorough mixture of a pulverized pavement (with or without new aggregate) with the correct quantity of stabilizer (if used) and sufficient fluids to permit maximum density during compaction. To achieve these ends equipment must be selected, operated and sequenced to provide the following:

1. Pulverization of recycled pavement material,
2. Proper water content (uniformly mixed),
3. Proper stabilizer content (uniformly mixed),
4. Attainment of some minimum specified density,
5. Favorable temperature and moisture conditions for strength development during the curing period and
6. Protection of the stabilized surface from traffic to prevent abrasion and to ensure adequate time for strength development.

Specifications. Guide specifications have been prepared for and are contained in Reference 1 for the following cold recycling operations (1):

1. In-Place Recycling of Existing Asphalt Surface and/or Existing Base (Subbase) Without Chemical Stabilization.
2. In-Place Recycling of Existing Asphalt Surface and/or Existing Base (Subbase) Employing Lime Stabilization.
3. In-Place Recycling of Existing Asphalt Surface and/or Existing Base (Subbase) Employing Portland Cement Stabilization.
4. In-Place Recycling of Existing Asphalt Surface and/or Existing Base (Subbase) Employing Asphalt Stabilizers.

Other specifications can be obtained from references cited in this report or from governmental agencies conducting cold recycling operations as identified herein.

A review of the specifications contained in the literature will indicate that they were largely developed from soil stabilization specifications and quality control guides. At present sufficient data are not available to develop statistically based quality assurance specifications for recycling operations. Potential quality control problem areas associated with cold recycling operations are:

1. Depth of pavement removal,
2. Degree of pulverization,
3. Control of additional binder,
4. Control of recycling agent, and
5. Distribution of additional binder and/or stabilizers.

Climatic and Safety Considerations. The use of lime, lime-fly ash, portland cement, cement-fly ash and asphalt stabilizers in cold recycling operations have certain climatic limitations and construction safety precautions. These limitations and precautions are listed on Table 4. Climatic limitations include minimum temperatures of about 40°F and sufficient time before the first freeze to prevent damage to newly stabilized layers. Flash and fire points should be considered when handling bituminous materials and protective clothing worn at all times when lime and portland cement are utilized.

Mixture Design

In-place and central plant cold recycling operations will often make use of chemical additives such as lime, portland cement, asphalt cement and/ or recycling agents to improve the engineering properties of the recycled materials. Selection of this type of additive or stabilizer and the amount for a given recycling project is of concern to the engineer. This section of the report describes a soil stabilization index system (SSIS) which was developed for the U. S. Air Force by Texas A&M University (33), later modified by the Air Force Academy (34) and utilized in a FHWA soil stabilization manual (24). This index system can be used to select the type and amount of stabilizer to be used for a given recycled material.

Type of Stabilizer. Figure 8 provides a stabilizer selection procedure based on the percent passing the No. 200 sieve and the plasticity index (PI). Based on these criteria it is evident that the majority of the cold recycling projects utilizing stabilizers will use either lime or bituminous materials. The use of bituminous materials may involve selection of an appropriate recycling agent (softening agent).

After an appropriate stabilizer or appropriate stabilizers are selected, design sub-systems can be used to select the amount of stabilizers. Appropriate test methods and criteria are briefly outlined for each type of stabilizer. Detailed information can be found in Reference 24. Design sub-systems for lime, portland cement and asphalt stabilization follow. Design sub-systems for lime-fly ash and cement-fly ash are contained in Reference 24.

Lime Stabilization. The design sub-system for stabilization with lime is shown in Figure 9. The procedures for the nonstandard tests are outlined in Reference 2.

The design curve for the freeze-thaw test and a correlation curve between three-cycle freeze-thaw strength and vacuum immersion strength are shown in Figures 10 and 11, respectively. The purpose of Figure 10 is to allow the interpolation of the freeze-thaw strength loss after a predicted number of freeze-thaw cycles from three freeze-thaw cycles in the laboratory.

The family of design curves in Figure 10 was developed from an extensive testing program (34). These curves showed that the additional strength loss after 7 cycles was negligible.

In using Figure 10, first determine the expected number of freeze-thaw cycles during the first winter after rehabilitation then interpolate along the appropriate design curve from the laboratory strength loss after 3 cycles to that after the appropriate number of freeze-thaw cycles (strength loss is the difference between the reactivity test strength and the strength after the freeze-thaw cycle).

Figure 11 allows use of vacuum immersion in lieu of freeze-thaw. The strength loss is determined as described above. Table 5 contains the minimum residual strength criteria that must be maintained.

Cement Stabilization. The modified SSIS cement design sub-system is as shown in Figure 12. The MacLean and Sherwood pH test discussed below is the only nonstandard test procedure employed. However, if a high sulfate content is suspected in the soil to be stabilized, a check on the amount of sulfate present should be made. An upper limit of 0.9 percent is set for sulfate content (33). The turbidimetric method used to determine sulfate content can be found in Reference 2. Because of the nature of the test it is only warranted when a high sulfate content is suspected.

After the soil cement mixture has been checked for deleterious organics content, standard PCA procedures are followed (36). In the base course procedure the wet-dry test is often much less severe than the well-established freeze-thaw test (34). Therefore, solely the PCA freeze-thaw weight loss criteria is suggested for use for base course design (Table 6).

Asphalt Stabilization. Asphalt binders present in recycled pavements often contain physical and chemical properties which make the "old" asphalt undesirable for reuse without modification. Materials have been developed to restore these old binders to a condition suitable for reuse. This concept is not new and has been the subject of a number of extensive studies during the last several years (37-44).

Materials used to alter properties of asphalt cements have been called softening agents, reclaiming agents, modifiers, recycling agents, fluxing oils, extender oils, aromatic oils, etc. Most of the major oil companies market products of this type will be used to designate this type of material in this report and originate from ASTM Subcommittee D4.37 (Modifier Agents for Bitumen in Pavements and Paving Mixtures). The general definition of modifier is "a material when added to asphalt cement will alter the physical-chemical properties of the resulting binder." A more specific definition has been developed by the Pacific Coast User-Producer Group for the term "recycling agent." A "recycling agent" is a hydrocarbon product with physical characteristics selected to restore aged asphalt to requirements of current asphalt specifications (45). It should be noted that soft asphalt cements, as well as specialty products, can be classified as recycling agents or modifiers.

The purpose of the modifier in asphalt pavement recycling is to:

1. Restore the recycled or "old" asphalt characteristics to a consistency level appropriate for construction purposes and for the end use of the mixture,
2. Restore the recycled asphalt to its optional chemical characteristics for durability,
3. Provide sufficient additional binder to coat any new aggregate that is added to the recycled mixture and
4. Provide sufficient additional binder to satisfy mixture design requirements.

The design method outlined below allows the engineer to select the types and amount of bituminous modifiers to produce the desired mixture (46).

The proposed method is applicable for both hot and cold recycling operations and includes modifiers such as softening agents, rejuvenators, flux oils and soft asphalt cements. The method consists of the following general steps:

1. Evaluation of salvaged materials,
2. Determination of the need for additional aggregates,
3. Selection of modifier type and amount,
4. Preparation and testing of mixtures and
5. Selection of optimum combinations of new aggretates and asphalt modifiers.

The overall philosophy of this approach is to utilize the recycled materials, new aggregate and modifier to produce a mixture with properties as nearly like a new asphalt concrete mixture as possible. Standard test methods have been utilized where possible. The mixture design procedure is shown in Figure 13 and has been modeled after that suggested in References 37 to 42. The circled numbers on the flow diagram refer to the steps presented below.

Field Samples (1). Representative field samples should be obtained from the pavement to be recycled. A visual evaluation of the pavement should be made together with a review of construction and maintenance records to determine significant differences in the material to be recycled along the pavement section. Roadway sections with significant differences in materials should not be lumped together because uniformity and predictability of results will be impaired. Locations within a project can be determined on a random basis using the procedure outlined in Reference 46. At least 5 or 6 locations should be used as a minimum and a total composite sample of about 200 lbs. is recommended for laboratory evaluation. If desired, core samples may also be obtained and used for comparison of original and recycled properties such as stability and resilient modulus (M_R) (47).

Extract and Recover Asphalt and Aggregate (2). Extraction and Recovery tests should be performed at each location sampled. Results of these tests (penetration, viscosity, asphalt content) together with thickness measurements made from the cores should help determine the uniformity of the section under consideration for recycling. Sufficient asphalt should be recovered to permit blending with asphalt modifiers for further testing.

Aggregate Properties (3). Aggregate recovered from the samples in step (2) above should be tested for gradation, durability such as Los Angeles Abrasion and Polish Value if the recycled mixture is to be utilized as a surface course. These data can be used to establish project uniformity together with the recovered asphalt data obtained in step (2).

New Aggregate (4). New aggregate may have to be added to the mixture for one or more of the following purposes:

1. Satisfy gradation requirements,
2. Skid resistance requirements for surface courses,
3. Air quality problems associated with hot, central plant recycling,
4. Thickness requirements and
5. Improved stability, durability, flexibility, etc.

Gradation requirements for recycled mixtures should be those presently required by the specifying agency or those in ASTM D3515.

To provide initial and long lasting skid resistance for the recycled bituminous surface course, it may be necessary to blend coarse non-polishing aggregate with the recycled pavement. It appears as if 40 percent by volume of the plus No. 4 fraction should be non-polishing to provide the desired skid performance on moderate to high traffic volume facilities.

Replacing the recycled pavement with a thicker section of asphalt stabilized material may be required from a structural pavement design standpoint. This can be accomplished by blending new aggregate with the recycled material or by the addition of layers of new asphalt stabilized materials.

Asphalt Demand (5). The asphalt demand of the proposed recycled material can be estimated from the following equation:

$$D_T = V_R D_R + V_N D_N \quad (1)$$

where:

$$D_R = D_{CKE} - A_R \quad (2)$$

and

D_R = asphalt demand for salvaged or recycled aggregate, percent

D_{CKE} = CKE derived Oil Ratios for salvaged or recycled aggregate, percent

A_R = asphalt content of salvaged or recycled aggregate

D_N = CKE derived Oil Ratios for new aggregate, percent

V_R = volume of recycled aggregate in mixtures

V_N = volume of new aggregate in mixtures

It should be noted that if new aggregate is not utilized, Equation 1 becomes Equation 2.

The asphalt demand determined in this manner should be considered an estimate and can be used as a starting point for mixture design purposes. It should be noted that the asphalt demand will be satisfied by the modifier as specified in Tables 7 and 8. These modifiers can be softening agents, asphalt cements or blends of softening agents and asphalt cements or emulsified products.

Asphalt Properties (6). Asphalt recovered from the samples in step (2) above should be tested for penetration at 77°F and viscosity at 140°F. Asphalt content, penetration and viscosity should be determined on all extracted samples. These data can be used to determine project uniformity

Determine Type and Amount of Modifiers (7) (8). The type and amount of modifiers can be selected by utilizing Figure 14 and Tables 1 and 2 (48) together with a definition of the penetration or preferable viscosity of the binder in the processed recycled mixture and a knowledge of the asphalt demand of the recycled mixture which was obtained in step (5), Equation 1. For example, assume the following:

1. CKE Oil Ratios on extracted salvaged or recycled aggregate, D_{CKE} = 5.0%
2. Percent asphalt in salvaged or recycled material, A_R = 4.0%
3. Viscosity of aged asphalt 20,000 poises
4. Additional new aggregate, V_N = 30%
5. CKE Oil Ratio of new aggregate, D_N = 6.0%
6. Desired viscosity of recycled asphalt = 2,000 poises

From Equations 1 and 2 the following asphalt demand can be calculated:

$$D_T = V_R D_R + V_N D_N \quad (1)$$

$$D_R = D_{CKE} - A_R \quad (2)$$

$$D_R = 5.0 - 4.0 = 1.0$$

$$D_T = (.70)\ (1.0) + (.30)\ (6.0)$$

$$D_T = 2.5\%$$

The maximum predicted percent modifier by weight of total binder in the recycled mixture is therefore:

$$\frac{D_T}{V_R A_R + D_T} \times 100$$

$$= \frac{25}{(.70)\ (4.0) + 2.5} \times 100$$

$$= 47\%$$

By use of Figure 14 the viscosity of the modifier can be approximated. The figure is entered with the volume percent of lower viscosity modifier (47%) and the desired viscosity of the recycled binder to locate Point A. Point A is connected with the viscosity of the recovered salvaged binder and the line projected to obtain the viscosity of the modifier. Table 1 indicates that modifier grade RA 5 would likely be suitable.

It should be noted that new asphalt cement and a softer modifier could be utilized to form the new binder provided air quality requirements can be met.

Modifier Tests (9). Samples of modifiers to be used on the job should be obtained and subjected to tests to establish their conformance to specifications (Table 7 or 8) as well as establish the viscosity of the modifier in order to obtain a more realistic modifier content (Figure 14).

Blend Modifier With Recovered Asphalt (10). The modifier which may consit of an asphalt cement and softener should be blended with the recovered asphalt and subjected to viscosity and penetration tests to determine if the precicted viscosity (penetration) of the blend was accurate. It is suggested that two blends, one 5% above and one 5% below the percent recycling agent determined in steps (7) and (8) be made. About 75 to 100 grams of recovered asphalt for each blend should be utilized. A third blend may be required to confirm the desired viscosity or penetration.

Some recycling base stock modifiers may not be compatible with the salvaged asphalt. Therefore, a thin film oven test should be performed on the selected recovered recovered salvaged asphalt-modifier blend. A ratio of the aged viscosity to original viscosity of less than 3 will indicate that the recycling agent is likely to be compatible with the recovered salvaged asphalt.

Preliminary Mixtures (11). Five different mixtures of recycled aggregate, new aggregate if desired, and modifier should be fabricated. Three samples of each mixture should be fabricated and subjected to stability testing and tests to determine the air void content. These preliminary tests should vary the percent new asphalt cement and/or the type and amount of modifiers. It is helpful to have an experienced engineer present during the mixing and molding operation as subsequent trial mixtures may depend upon the appearance of the first few trial mixtures. It should be realized that the modifiers often have a delayed softening reaction.

Standard mixing and molding operations should be utilized. An oven curing procedure after mixing and prior to compaction such as that used in California appears to be desirable.

Detailed Mixture Evaluations (12). The three most promising mixtures evaluated in step (11) should be evaluated in detail for properties which can be used in pavement thickness design and for durability considerations such as water susceptibility. The testing plan as shown in Figure 15 can be used as a guide. The amount of testing will depend upon the capability of the agency considering the recycling project. However, the authors feel that extraction and recovery tests are important as well as resilient modulus tests.

Properties of the extracted and recovered bituminous material from the laboratory prepared and recycled mixture are an indication of the compatibility and durability of the recycling modifiers. Preliminary laboratory testing has indicated that extraction and recovery tests will identify potential problems between the "old" asphalt and the modifier that tests performed on the blend of "old" asphalt and modifier do not identify.

The resilient modulus appears to be the best single test to identify the effect of the modifier on the mixture. This test is sensitive to the properties of the binder and will help define the amount of modifier required to produce a binder of known consistency. Resilient modulus values of the order of 200,000 to 400,000 psi (measured at 77°F, 0.0 record load duration) are typical of recycled mixtures blended with modifiers to produce binders equivalent to AC-10 asphalt cements.

Select Optimum Mixture Design (13). The optimum mixture design should be based on results of steps (11) and (12) and economic and energy considerations. Reference 46 can be used as a general guide. In general, final mixture designs should be based on stability requirements and air void criteria; however, the resilient modulus versus temperature relationship shoul be considered. The resilient modulus versus temperature relationship should be considered. The resilient modulus should be below about 900,000 psi (77°F and 0.1 second load duration).

Mixture Containing Emulsified Modifiers. The above discussion has been primarily directed toward the use of recycling agents specified in Table 7 in cold operations. Recycling in central plants or in place with emulsified modifiers is also an alternative that is considered one number of projects. The design of mixtures containing emulsions required special considerations as outlined below:

1. The properties of the base modifier should be used in step (7) to determine the type and amount of emulsified modifier to be used
2. The modifier sample tested in step (9) should be subjected to those tests required for specification compliance. Table containes an example specification for emulsified modifiers,
3. The base modifier should be used for the blends prepared in step (10). Tests should be performed as outlined in step (10),
4. Mixing and testing of recycled mixtures containing emulsified modifiers should be performed according to procedures outlined in Reference 49. Of the 11 methods identified in the reference it is suggested that The Asphalt Institute Method be utilized. Curing of the samples prior to testing is critical and should be closely followed and
5. Criteria for mixture designs are shown in Table 9. These criteria should be used on an interim basis.

Pavement Design

Pavements containing cold recycled layers should be designed using methods which are capable of considering the load carry capability of stabilized materials. Design procedures advanced by the American Association of State Highway and

Transportation Officials (AASHTO) (50), U. S. Forest Service (51), The Asphalt Institute (52), Arizona, California, Illinois, Louisiana, New Mexico, Ohio, Texas, Utah (53) and Wyoming have developed procedures in which pavement layer coefficients are utilized for thickness determination.

Layered elastic approaches can also be utilized for the design of pavements containing cold recycled materials. Methods available for use in manual form include those developed by Chevron (54), Shell (55) and the Federal Highway Administration. Reference 56 contains descriptions of these methods and is a good reference for pavement design.

Because of its general widespread acceptability and use the AASHTO method of pavement design has been utilized in this paper. A brief description of the method follows.

AASHTO Method. The AASHTO design procedure is based on the AASHTO Road Test in Ottawa, Illinois, and on latter satellite programs. The "AASHTO Interim Guide for Design of Pavement Structures, 1972" (50) along with National Cooperative Highway Research Program (NCHRP) Report 128 which reports on data accumulated by State Highway Departments since 1961 (57) and Highway Research Board Special Report 73 (58) form the background for the procedure.

Figure 16 shows the nomograph solution to the pavement design equations resulting from the AASHTO Road Test and with terminal serviceability index values (P_E) values of 2.0 and 2.5. The nomograph solution is obtained by first finding the unweighted structural number ($\overline{SN}$) on the center scale for a given soil support value (S) and total equivalent 18-kip single axle loads (W_{t18}). The unweighted structural number value is then corrected by the regional factor (R) to determine the required design structural number (SN). The structural number can then be utilized to calculate pavement layer thicknesses. A description of each term associated with the nomographic and the method used to determine pavement layer thicknesses follows.

Terminal Serviceability. As noted in the design nomograph, commonly used values of the terminal serviceability are 2.0 and 2.5. The p_t value is the lowest serviceability that will be tolerated on the road at the end of the traffic analysis period before resurfacing or reconstruction is warranted. For major highway facilities a value of 2.5 is recommended while a p_t = 2.0 is suggested for lesser traffic volume roads. Normally it is recommended that the p_t value selected should never be less than 2.0. For minor highways, the approach is to keep p_t = 2.0 but reduce the traffic analysis time period.

Soil Support Value (S). The arbitrary manner in which the soil support scale was introduced into the AASHTO design procedure is discussed in the literature (57, 58). Because this input value (S) cannot be directly obtained by testing, each design agency using the guide must establish correlations between standard soil tests (e.g., CBR, R, triaxial strength) and soil support value. Figure 17 illustrates such a correlation. Figure 17a is based on a Utah study while 17b is based on a layered elastic study (57). A close examination of these two studies shows that even though the two are in fairly good general agreement, differences in (S) for a given soil test procedure do occur. This fact illustrates the obvious necessity to use as much engineering judgement as possible with the selection of the soil support value.

Equivalent Wheel Load Repetition (W_{t18}). For the AASHTO design method, mixed traffic within a given period of time (termed the traffic analysis period) is accounted for by equivalent damage factors relative to the standard 18-kip single-axle load (see Reference 56, Chapter 4).

Traffic may be equated to daily 18-kip load applications if a common 20-year traffic analysis period is selected or it may be expressed as the total 18-kip load applications within the traffic analysis period. Equivalency factors, and hence W_{t18} applications, are a function of p and SN. For most design problems, an SN value of 3.0 may be assumed for the equivalency analysis. This value will normally result in an overestimation of the W_{t18} but in general, the resulting error will be insignificant.

Regional Factor. The regional factor was placed into the AASHTO design procedure to allow for its use in climatic environments other than the one that existed during the Road Test. In its present form, the R value constitutes a fairly significant input value but unfortunately is one that, at present, is not well documented. Based upon an analysis of the Road Test results dealing with the rate of loss of serviceability during various climatic periods during various climatic periods during the testing, typical values of R were developed by the AASHTO guide. These values are shown in Table 10. Based on an NCHRP state evaluation study of the AASHTO design guide (57), a generalized R value contour map has been developed for the U. S. (Figure 18). In most cases, the selection of the proper R value must be based upon the local conditions of the highway in combination with the judgement of an experienced engineer. The recommended range in R by the AASHTO design guide for U. S. conditions is from 0.5 to 4.0.

Structural Number (SN). The SN is defined as an index number derived from an analysis of traffic, road-bed soil conditions, and regional factor that may be converted to thickness of various flexible-pavement layers through the use of suitable layer coefficients related to the type of material being used in each layer of the pavement structure. The layer coefficient (designated by a_1, a_2, and a_3, for surface, base and subbase, respectively) is the empirical relationship between SN for a pavement structure and layer thickness, which expresses the relative ability of a material to function as a structural component of the pavement (50).

Analytically, the SN is given by

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

where the D_1 values are the respective layer thicknesses.

At the AASHTO Road Test, four types of basic materials were used in the study: crushed stone, gravel, cement-treated gravel, and bituminous-treated gravel. Based upon the results of the study along with an estimation from results of special base studies at the test, layer coefficients were established by the AASHTO Committee on Design and are shown in Table 10.

Since the initial publication of the layer coefficients, several state highway departments and trade agencies have developed their own layer coefficients for materials commonly used by their respective agencies. Based upon the NCHRP evaluation study of the AASHTO design guide (57), nomographic solutions of the layer coefficients have been proposed from a combined analysis of individual state highway results and a theoretical multilayered elastic analysis. These nomographs are shown in Figure 19 and are presented as guides in assessing relative changes in the a_1 values as the measured test response of the material varies.

Since the solution of the AASHTO equation in a design, SN, it should be realized that any combination of layer thicknesses and material types satisfies the design equation. However, Van Til, et al. (57) have advocated that, since the flexible pavement is a layered structure, each layer must be checked to insure that an adequate thickness of proper material is provided as cover. This logic parallels that of the CBR design method in which the thickness of pavement above any specific layer must be such that excessive stresses (greater than the strength) do not occur in that layer.

Figure 20 illustrates the suggested procedure for checking the pavement design on this layered concept. In essence, the procedure is to select appropriate S_1 values for each layer and then compute the required SN_1 value from the design equation or nomograph. By using the differences in SN between the computed SN required over each layer, the minimum allowable thickness of any given layer must be obtained.

Minimum Layer Thicknesses. The suggested minimum layer thicknesses for surface, base and subbase course are 2, 4 and 4-inches, respectively. These minimums are based primarily upon construction and maintenance considerations. Obviously, the minimum thickness for the subbase layer is only applicable when such a layer is used in the pavement structure.

Coefficients for Recycled Materials. From the above discussion it is apparent that determination of layer coefficients for cold recycled materials is important if pavement structures are to be designed properly. Since cold recycling produces materials very similar to those produced by conventional stabilization operations, a summary of coefficients has been prepared for stabilized materials and is shown in Table 12. Layer coefficients for recycled materials have been recently calculated at Texas A&M University (2, 59, 60, 61). Table 13 presents a summary of these data obtained for various types of recycling operations. Structural coefficients for cold recycled materials containing bituminous binders are shown in Table 14. These coefficients were determined from laboratory measured properties of field cores according to the method explained in References 2 and 20.

Table 15 contains structural coefficients for cold recycled materials containing lime, cement, asphalt and SA-1 binders. These coefficients were determined from in-situ deflection testing according to the methods explained in References 2 and 20. Structural ratios based on stiffness of cold recycled materials are shown in Table 16 (2, 60).

It should be recognized that the structural layer coefficient is not only dependent on the material properties of the layer in question but also on the material properties of the other layers in the system, the thicknesses of the other layers and the material properties of the subgrade. In turn, since the elastic material properties of the other layers may be either stress sensitive, temperature sensitive or both, the structural coefficients are also a function of the type and magnitude of loading and the climate.

Properties of Cold Recycled Materials. Typical properties of cold recycled materials are available in the literature and unfortunately have been reported on a job by job basis. Preparation of a summary table of these data would be almost meaningless because of the variety of molding, curing and testing techniques utilized by the various agencies. Data are, however, being generated at Chevron, Purdue University and Witco Chemical (among others) for a wide range of materials. Comparison of these data which are not available in the literature indicates that cold recycling materials can be produced which meet the commonly accepted criteria used for stabilized soils.

Resilient moduli data have been obtained on a number of core samples obtained from cold recycled pavements in California, Kansas and Texas. These data were obtained over a temperature range and are reported in Reference 2. Figures 21 to 25 illustrate typical results for cement, cut-back and emulsion stabilized projects. It is interesting to note that low percentages of cement introduced into mixtures does not greatly effect the temperature dependence of the resulting recycled mixture.

Economics and Energy

Selection of the most appropriate rehabilitation or maintenance alternative for a particular project is largely dependent upon cost and energy comparisons. A method for selecting appropriate recycling operations for a given job has been outlined by Finn (62) at this conference while Halstead (63) has defined cost and energy considerations associated with project selection. Cost and energy data associated with recycling operations will be included in summary form for completeness.

Cost Considerations

The initial and recurring costs that an agency may consider in the economic evaluation of alternative rehabilitation strategies have been defined in Reference 64 and include the following:

1. Agency costs
   a. Initial capital costs of rehabilitation,
   b. Future capital costs of reconstruction or rehabilitation (overlays, seal coats, etc.),
   c. Maintenance costs, recurring throughout the design period,
   d. Salvage return or residual value at the end of the design period,
   e. Engineering and administration and
   f. Costs of investments.
2. User costs
   a. Travel time,
   b. Vehicle operation,
   c. Accidents,
   d. Discomfort and
   e. Time delay and extra vehicle operating costs during resurfacing or major maintenance.
3. Nonuser costs

Certainly all of these costs should be included if a detailed economic analysis is desired. However, definition of many of these costs is difficult while other costs do not significantly affect the analysis of alternatives for a given roadway segment. For the sake of simplicity the method of analysis suggested for use in recycling operations should consider the following costs:

1. Initial capital costs of rehabilitation,
2. Future capital costs of reconstruction or rehabilitation,
3. Maintenance costs and
4. Salvage value.

It is suggested, however, that certain user costs such as time delay costs during rehabilitation be considered on high traffic volume facilities. The reader is directed to Reference 64 for additional detail.

Initial capital costs of various recycling operations are available from Reference 2 and are shown in Tables 17 and 18. Costs of common construction and rehabilitation operations are shown in Tables 19 and 20.

The cost figures given above are intended to be representative only. If cost data are available from the agencies historical records, they should be substituted appropriately.

Energy Considerations

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

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

Information given in Table 21 defines energy requirements for recycling operations. These energy requirements are intended to be representative only. If energy requirements for these operations are available from the agencies' historical records, they should be substituted appropriately. Energy requirements for typical construction and reconstruction operations can be found in Reference 2.

Case Histories and Example Project

Case Histories. Cold recycling case histories will be presented in papers prepared by Canessa (48) and Spelman (65). In addition Reference 1 contains a summary of over 10 cold recycling projects located throughout the United States, performed with a variety of different types of equipment and utilizing several different construction operation sequences. A partial list of recycling projects together with appropriate references are given in Table 22. Review of this literature will be encouragement for those individuals planning their first cold recycling project.

Example Project. An existing highway in central Nevada presently carries 50 daily equivalent 18-kip single axle loads. The pavement has extensive alligator cracking in the wheel path and transverse and longitudinal cracks. The pavement was constructed in 1954 with a six-inch crushed gravel base and two inches of asphalt concrete. The R value of the subgrade material is 8.

Deflection measurements have been made along the 6-mile project and samples of the material have been obtained. Overlay design methods based on deflection measurements indicate that a 4-inch asphalt concrete overlay is required.

The pavement is located a considerable distance from a central hot mix plant and cold recycling with an asphalt emulsion is being considered.

Based on Figure 16 and with the following assumptions;

1. Soil support = 4 (Figure 17a)
2. Daily equivalent 18-kip axle loads = 50 (given)
3. Regional factor = 1 (Figure 18)
4. Terminal serviceability index = 2.5 (assumed)

a structural number (SN) of 3.1 can be calculated. An acceptable cold recycled pavement section that will provide this structural number is given below:

1. Surface treatment (chip seal)
2. Nine inches of cold recycled surface, base and new aggregate

The structural layer coefficient has been assumed to be 0.35 (Table 13) for the recycled material; thus, the structural number provided by the section is 3.15 (9 x 0.35).

The anticipated cost of the recycled pavement section is

Surface treatment = 0.45 (Table 19)
Recycled material (9 x 0.60) = 5.40 (Table 17)
Total = 5.85 per square yard

Due to the remote location and the long haul required for the aggregates, hot mix is expected to cost \$30 per ton in-place. The cost of the 4-inch overlay would be \$6.00 per square yard. In addition, it is expected that the shoulder work required for the overlay would be equivalent to adding another \$1.50 per square yard to the cost of the job.

Energy requirements associated with the two alternatives can be calculated as shown below:

Cold Recycling Alternative
Surface treatment = 4,000 (Reference 2)
Recycled material 9 x 17,000 = 153,000 (Table 21)
Total = 157,000 Btu per square yard

Overlay Alternative
Asphalt concrete 4 x 28,000 = 112,000 (Reference 2)
Shoulder work = 42,000 (estimated)
Total = 154,000 Btu per square yard

It is important to realize that the comparison of alternatives based on cost should be over their life. Life cycle costing techniques are defined and worksheets are available in Reference 2.

Mixture designs using emulsions can be performed as outlined in this paper. As stated above Reference 49 is an excellent guide to assist in selection of the emulsion content. Since the amount of binder in the old surface is small compared to the total binder requirements for the 9-inch recycled layer it is doubtful if the hardness of the old asphalt should be considered in the selection of the emulsion.

Conclusion

Cold recycling offers several advantages. Equipment required for the process is minimal and processing in-place affords the opportunity to correct structural and material problems quickly and, therefore, without prolonged disruption of traffic. Where an existing asphalt concrete course is pulverized and mixed together with the existing aggregate base, the residual asphalt acts as an excellent binder to help make the recycled base waterproof and less frost susceptible. The addition of new binder or chemical stabilizer, such as lime or cement, may further up-grade the recycled base by reducing swell potential where active clays are present in the base, by reducing freeze-thaw potential, by waterproofing the base aggregate and/or by increasing the load carrying capacity of the pavement structure.

With an increased load-carrying capacity in the base course, the pavement structure may be constructed thinner. A thinner pavement structure could 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 can be sold or stockpiled for future use.

Generally the equipment required for in-place recycling is of the basic road building type and is, therefore, available at almost any location. Furthermore, since in-place recycling is quite versatile in terms of the equipment required and the construction sequence, the engineer can tailor the operation to handle any peculiarities of the project. Since the equipment required is widely used, equipment operators are readily available.

The binders most widely used to upgrade the existing base aggregate (i.e., liquid asphalt, lime, cement, and fly ash) are usually acquired economically. In addition, the agencies associated with these products (The Asphalt Institute, the National Lime Association, the Portland Cement Association) provide detailed construction procedures and suggestions for optimizing the benefits from the use of these binders.

Major items of present concern should be recognized. These are stated very briefly below:

1. Reliability and productivity of pulverization and mixing equipment.
2. Uniformity of distribution of stabilizers and/or recycling agents.
3. Uncertain strength gain associated with cold recycled materials.
4. Rate of softening of the old asphalt cement by the emulsified recycling agents.

Obviously many of these concerns are common to soil stabilization.

The ultimate decision as to the application of in-place recycling is based on a total evaluation considering user utility, structural requirements, energy expenditures, and cost.

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Table 1. Major advantages and disadvantages of recycling techniques

Recycling Techniques	Advantages	Disadvantages
Surface	• Reduces frequency of 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 due to compaction • Treats a variety of types of pavement distress (raveling, flushing, corrugations, rutting, oxidized pavement, faulting) at a reasonable initial cost • Improve skid resistance	• Limited structural improvement • Heater-scarification and heater-planing has 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 • Limited disruption to traffic
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 • Improve skid resistance • Minimizes hauling	• Quality control not as good as central plant • Traffic disruption • Pulverization equipment in need of frequent repair • PCC pavements cannot be recycled in-place • Curing is often required for strength gain
Central	• Significant structural improvements • Treats all types and degrees of pavement distress • Reflection cracking can be eliminated • Improve skid resistance • Frost susceptibility may be improved • Geometrics can be more easily altered • Improved quality control if additional binder and/or aggregates must be used • Improve ride quality	• Potential air quality problems at plant site • Traffic disruption

After reference 2.

Table 2. Road and Street Mileage in the United States Classified by Type of Surface-1978.

Type of Surface		Mileage	Percent of Total Mileage
Non-Hard Surfaced	Unimproved	283,976	7.3
	Graded and Drained	397,986	10.2
	Soil and Rock	1,192,052	30.7
	Total	1,874,052	48.2
Hard Surfaced	Bituminous Low Strength	1,078,382	27.8
	Bituminous High Strength	811,553	20.9
	PCC*	120,812	3.1
	Total	2,010,747	51.8
Total Mileage		3,884,761	100.0

*Portland cement concrete with or without asphalt concrete overlay

After reference 21.

Table 3. Equipment Typically Associated with Mixed-In-Place Subgrade Stabilization Operations.

STABILIZER	CONSTRUCTION OPERATION				
	SOIL PREPARATION	STABILIZER APPLICATION	PULVERIZATION AND MIXING	COMPACTION	CURING
Lime[1]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc Harrow •Other agricultural-type equipment	•Dry-bagged •Dry bulk •Slurry •Slurry thru mixer	•Single- and multi-shaft rotary mixers •Motor graders •Other agricultural-type equipment	•Sheep's foot •Pneumatic •Steel wheel	•Asphalt membrane •Water sprinkling
Lime or cement, Fly ash[2]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc harrow •Other agricultural-type equipment	•Separate application •Lime--dry or slurry •Fly ash--conditioned •Combined application •Dry-bagged •Dry bulk	•Same as lime	•Steel wheel •Pneumatic •Vibratory	•Asphalt membrane •Water sprinkling
Cement[3]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc harrow •Other agricultural-type equipment	•Dry-bagged •Dry bulk	•Same as lime	•Sheep's foot •Pneumatic (clay soils) •Vibratory (granular soils)	•Asphalt membrane •Water sprinkling
Asphalt[4]	•Motor grader •Single-shaft rotary mixer (flat type)	•Asphalt spray distributor •During mixing process	•Single- and multi-shaft rotary mixer (flat type) •Motor grader	•Pneumatic •Steel wheel •Vibratory	•Volatiles should be allowed to escape and/or the pavement to cool

	COMMENTS	SAFETY PROCEDURES
1	Double application of lime may be required to facilitate mixing. The soil and air temperature should be greater than 40°-50°F to insure adequate strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Lime spreading should be avoided on windy days. Proper clothing should be worn so that workmen can avoid skin contact with quicklime. Workmen should avoid prolonged contact with lime and breathing lime dust.
2	Fly ash must be conditioned with moisture prior to distribution to prevent dusting. Mixing and compaction should be completed shortly after stabilizer application. The soil and air temperature should be greater than 40°-50°F to insure adequate strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist thaw-freeze action.	Fly ash, lime and cement spreading should be avoided in windy days. Workmen should avoid prolonged contact with the stabilizers and breathing the stabilizers.
3	Mixing and compaction must be completed shortly after stabilizer application. The soil and air temperatures should be greater than 60°F to insure an adequate rate of strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Cement spreading should be avoided on windy days. Workmen should avoid prolonged contact with cement and breathing the cement dust.
4	Proper soil moisture content must be achieved to aid distribution and mixing. Stabilized material should be properly aerated prior to compaction. The soil and air temperature should be above 40°F to allow for proper curing and sufficient time for compaction if hot mix processes are utilized. Thick lifts of hot, asphalt cement stabilized materials can be placed below 32°F.	Proper clothing should be worn so that workmen can avoid skin contact with quicklime.

After reference 24.

Table 4. Climatic Limitations and Construction Safety Precautions.

Type of Stabilizer	Climatic Limitations	Construction Safety Precautions
Lime and Lime-Fly Ash	Do not use with frozen soils Air temperature should be 40 F (5 C) and rising Complete stabilized base construction one month before first hard freeze Two weeks of warm to hot weather are desirable prior to fall and winter temperatures	Quicklime should not come in contact with moist skin Hydrated lime [$Ca(OH)_2$] should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times.
Cement and Cement-Fly Ash	Do not use with frozen soils Air temperature should be 40 F (5 C) and rising Complete stabilized layer one week before first hard freeze	Cement should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times
Asphalt	Air temperature should be above 32 F (0 C) when using emulsions Air temperatures should be 40 F (5 C) and rising when placing thin lifts (1-inch) of hot mixed asphalt concrete Hot, dry weather is preferred for all types of asphalt stabilization	Some cutbacks have flash and fire points below 100 F (40 C) Hot mixed asphalt concrete temperatures may be as high as 350 F (175 C)

1 in. = 2.54 X 10^{-2} mm.

After reference 24.

Table 5. Tentative Short-Term Soil-Lime Mixture Compressive Strength Requirements.

Anticipated Use	Residual Strength Requirement, PSI
Modified Subgrade	20
Subbase	
Rigid Pavement	20
Flexible Pavement	
Thickness of Cover	
10 Inches	30
8 Inches	40
5 Inches	60
Base	100

After reference 35.

Table 6. Criteria for Soil-Cement as Indicated by Wet-Dry and Freeze-Thaw Durability Tests

AASHTO Soil Group	Unified Soil Group	Max. Allowable Weight Loss - Percent
A-1-a	GW, GP, GM, SW, SP, SM	14
A-1-b	GM, GP, SM, SP	14*
A-2	GM, GC, SM, SC	14
A-3	SP	14
A-4	CL, ML	10
A-5	ML, MH, CH	10
A-6	CL, CH	7
A-7	OH, MH, CH	7

*10% is maximum allowable weight loss for A-2-6 and A-2-7 soils.

Additional Criteria:

1. Maximum volume changes during durability test should be less than 2 percent of the initial volume.
2. Maximum water content during the test should be less than the quantity required to saturate the sample at the time of molding.
3. Compressive strength should increase with age of specimen.

After reference 24.

Table 7.- Proposed Specifications for Hot Mix Recycling Agents[1].

	ASTM Test Method	RA 5 Min.	RA 5 Max.	RA 25 Min.	RA 25 Max.	RA 75 Min.	RA 75 Max.	RA 250 Min.	RA 250 Max.	RA 500 Min.	RA 500 Max.
Viscosity @ 140°F, cSt	D 2170 or 2171	200	800	1000	4000	5000	10000	15000	35000	40000	60000
Flash Point COC, °F	D 92	400	-	425	-	450	-	450	-	450	-
Saturates, wt. %	D 2007	-	30	-	30	-	30	-	30	-	30
Residue from RTF-C Oven Test @ 325°F	D 2872[2]										
Viscosity Ratio[3]	-	-	3	-	3	-	3	-	3	-	3
RTF-C Oven Weight Change ± %	D 2872[2]	-	4	-	4	-	2	-	2	-	2
Specific Gravity	D 70 or D 1298	Report		Report		Report		Report		Report	

1. The final acceptance of recycling agents meeting this specification is subject to the compliance of the reconstituted asphalt blends with current asphalt specifications.

2. The use of ASTM D 1754 has not been studied in the context of this specification, however, it may be applicable. In cases of dispute the reference method shall be ASTM D 2872.

3. $\text{Viscosity Ratio} = \dfrac{\text{RTF-C Viscosity at 140°F, cSt}}{\text{Original Viscosity at 140°F, cSt}}$

After Reference 48.

Table 8. Interim Specifications for Emulsified Modifiers.

Property	Function and Purpose	Test Method	Specifications
Viscosity @ 77°F, SFS	Ease of Handling	ASTM D 244-76	15-85
Pumping Stability	Prevention of Premature Breaking	G.B. Method(2)	Pass
Emulsion Coarseness, Percent	Optimal Distribution	Sieve Test, ASTM D 244-76 (MOD(3)	0.1 Max.
Sensitivity to Fines, Percent	Adequate Mixing Life	Cement Mixing, ASTM D 244-76	2.0 Max.
Particle Charge	Preferential affinity to Asphalt	ASTM D 244-76	Positive
Concentration of Oil Phase, Percent	Assurance of Oil Content and for Calculations	ASTM D 244-76 (MOD)(4)	60 Min.

1. Oils used for emulsions must meet specifications listed in Table 7.

2. Pumping stability is determined by charging 450 ml of emulsion into a one-liter beaker and circulating the emulsion through a gear pump (Roper 29,B22621) having 1/4" inlet and outlet. The emulsion passes if there is no significant oil separation after circulating ten minutes.

3. Test procedure identical with ASTM D 244 except that distilled water shall be used in place of two percent sodium oleate solution.

4. ASTM D 244 Evaporation Test for percent of residue is modified by heating 50 gram sample to 300°F until foaming ceases, then cooling immediately and calculating results.

After Reference 48.

Table 9. Test Methods.

Test Method		Base or Temporary Surface		Permanent Surface	
		Dense Graded	Open Graded	Dense Graded	Open Graded
Coating, %		50 min.	50 min.	75 min.	75 min.
Run-off, % Residual Asphalt		N. A.	0.5 max.	N. A.	0.5 max.
Wash-off, % Residual Asphalt		N. A.	0.5 max.	N. A.	0.5 max.
Combined (Run-off and Wash-off), %		N. A.	0.5 max.	N. A.	0.5 max.
Resistance R_t-Value	Early Cure*	70 min.	N. A.	N. A.	N. A.
@ 73 ± 5°F (23 ± 2.8°C)	Fully Cured + Water Soak**	78 min.	N. A.	N. A.	N. A.
Stabilometer S-Value @ 140 ± 5°F** (60 ± 2.8°C)		N. A.	N. A.	30 min.	N. A.
Cohesiometer C-Value @ 73 ± 5°F (23 ± 2.8°C)	Early Cure*	50 min.***	N. A.	N. A.	N. A.
	Fully Cured + Water Soak**	100 min.***	N. A.	N. A.	N. A.
Cohesiometer C-Value @ 140 ± 5°F** (60 ± 2.8°C)		N. A.	N. A.	100 min.	N. A.

*Cured in the mold for a total of 24 hours at a temperature of 73 ± 5°F (23 ± 2.8°C).

**Cured in the mold for a total of 72 hours at a temperature of 73 ± 5°F (23 ± 2.8°C) plus vacuum disiccation.

***Applicable to temporary wearing surface only.

Note: Besides meeting the above requirements, the mix must be reasonably workable (i.e., not too stiff or sloppy).

After Reference 13.

Table 10. Regional Factors[a]

Condition	R Value
Roadbed materials frozen to depth of 5 in. or more	0.2-1.0
Roadbed materials dry, summer and fall	0.3-1.5
Roadbed materials wet, spring thaw	4.0-5.0

[a]From AASHTO Interim Guide (50).

Table 11. Structural Layer Coefficients Proposed by AASHO Committee on Design,[a] October 12, 1961

Pavement Component	Coefficient[b]
Surface course	
Roadmix (low stability)	0.20
Plantmix (high stability)	0.44*
Sand asphalt	0.40
Base course	
Sandy gravel	0.07[c]
Crushed stone	0.14*
Cement-treated (no soil-cement)	
Compressive strength @ 7 days	
650 psi or more[d]	0.23[c]
400 psi to 650 psi	0.20
400 psi or less	0.15
Bituminous-treated	
Course-graded	0.34[c]
Sand asphalt	0.30
Lime-treated	0.15-0.30
Subbase course	
Sandy gravel	0.11
Sand or sandy clay	0.05-0.10

*Established from AASHO Road Test data

[a]From AASHO Interim Guide (50).

[b]It is expected that each state will study these coefficients and make such changes as experience indicates necessary.

[c]This value has been estimated from AASHO Road Test data, but not to the accuracy of those factors marked with an asterisk.

[d]Compressive strength at 7 days.

Table 12. Structural Layer Coefficients Developed from Various Sources.

STABILIZER	LAYER	MATERIAL	COEFFICIENT (note)
Asphalt	aSurface	Road mix (low stability) Plant mix (high stabil.) Sand asphalt	0.20(a) 0.15(k) 0.44(B) 0.30(h) 0.25 - 0.34(i) 0.30(k) 0.40(a,d,n) 0.20(h) 0.25(e) 0.28(g)
	bBase	Bituminous treated coarse graded sand asphalt Sand gravel Asphalt stabilized	0.175 - 0.21(g) 0.34(a,b) 0.24(m) 0.30(d) 0.30(a) 0.25(d) 0.25 - 0.34(e) 0.10(f)
Untreated	bBase	Sandy gravel Crushed stone	0.17(a,b) 0.14(*)
	cSubbase	Sandy gravel Sand or sandy clay	0.11(*) 0.05 - 0.10(a)
Lime	bBase	Lime-treated	0.15 - 0.39(a,n) 0.15 - 0.20(h)
	cSubbase	Lime-treated clay-gravel Lime-treated soil	0.18(c) 0.14 0.11(p)
Lime - Fly ash	bBase	Lime - Fly ash base	0.25 - 0.30(c)
Cement	bBase	7-day compressive strength: 650 psi or more 400-650 psi 400 psi or less Soil cement Gravel Cement-treated	 0.23(a,b,n,k) 0.20(a,n) 0.17(k) 0.15(a,n) 0.12(k) 0.20(f,l) 0.17(j) 0.15 - 0.25(p)

1 psi = 6.89×10^3 Pa

Notes for Table 12

* Established from AASHO Road Test

a From AASHO Interim Guide, 1972 (50)

b This value has been estimated from AASHO Road Test data, but not to the accuracy of those marked with an asterisk.

c NCHRP Synthesis of Highway Practice, No. 37, "Lime-Fly Ash-Stabilized Bases and Subbases." (57)

d Alabama (from a above)

e Arizona (from a above)

f Deleware

g Minnesota

h Montana

i Nevada

j New Hampshire

k New Mexico

l Pennsylvania

m South Dakota

n Wisconsin

p Wyoming

Table 13. Typical AASHTO Structural Layer Coefficients

Type of Recycled Material	Layer Used as	Range of a_1 Computed	Average a_1	Number of Test Sections	a_1 for Corresponding Layer and Material at AASHTO Road Test
Central Plant Recycled Asphalt Concrete Surface	Surface	0.37-0.59	0.48	14	0.44
Central Plant Recycled Asphalt Concrete Base	Base	0.37-0.49	0.42	3	0.35
In-Place Recycled Asphalt Concrete Stabilized with Asphalt and/or an Asphalt Modifier	Base	0.22-0.49	0.39	6	0.35
In-Place Recycled Asphalt Concrete and Existing Base Material Stabilized with Cement	Base	0.23-0.42	0.33	4	0.15-0.23
In-Place Recycled Asphalt Concrete and Existing Base Stabilized with Lime	Base	0.40	0.40	1	0.15-0.30
In-Place Recycled Asphalt Road Mix Stabilized with Asphalt	Surface	0.42	0.42	1	

After reference 60.

Table 14. Structural Coefficients of Recycled Bases Where the Recycled Bases were Stabilized with a Bituminous Binder (Characterized by Diametral Resilient Modulus versus Temperature).

Recycled Base	Description of Recycled Base	Reference Base Thickness, Inches		Compute a_2	
18th Avenue, Le Moore, California	Crushed AC + 3.5% Cyclogen (Rejuvenator)	4 8 12	 avg.	0.46 0.42 0.38	 0.38
Russel Avenue, Fresno County California	Crushed AC + 1.1% Cyclogen (Rejuvenator)	4 8 12	 avg.	0.42 0.38 0.36	 0.35
U.S. Highway 56, Pawnee Co., Kansas (Section 2)	Crushed AC + 1.6% Cement and 3.8% Water	4 8 12	 avg.	0.43 0.38 0.34	 0.34
U.S. Highway 56, Pawnee Co., Kansas (Section 3)	Crushed AC + 1% MC - 800	4 8 12	 avg.	0.39 0.36 0.32	 0.33
U.S. Highway 56, Pawnee Co., Kansas (Section 4)	Crushed AC + 1.5% Cement + 1.6% AC - 7 and 4% Water	4 8 12	 avg.	0.40 0.39 0.33	 0.33
Trunk Highway 94, Minnesota	Crushed AC + Existing Base + 2.6% AC	4 8 12	 avg.	0.60 0.45 0.41	 0.42
I20, Roscoe, Texas	Crushed AC + Existing Base + 2.8% AC - 3	4 8 12	 avg.	0.45 0.40 0.36	 0.37
U.S. Highway 84, Snyder, Texas	Crushed AC + Base + 5% Asphalt Emulsion (Section 1)	4 8 12	 avg.	0.56 0.51 0.48	 0.49

After reference 2.

Table 15. Structural Coefficients of Recycled Bases Where the Recycled Layer was Characterized by In-Situ Dynamic Testing.

Recycled Base	Description of Recycled Base	In-Situ Dynamic Modulus, psi	Reference Base Thickness, Inches	Computed a_2
Ponderosa Avenue, Inclined Village, Nevada	Crushed AC + Existing Base + Cement (Approx. 4%)	190,000	4 8 12 Avg.	0.34 0.31 0.27 0.26
U.S. Highway 50, Dayton, Nevada	Crushed AC + Existing Base + Cement (Approx. 2.6%)	120,000	4 8 12 Avg.	0.29 0.26 0.23 0.23
U.S. Highway 93, Wells, Nevada	Crushed AC + Existing Base + Cement (Approx. 2.6%)	700,000	4 8 12 Avg.	0.49 0.46 0.42 0.42
Highway 45, Yolo, California	Crushed AC + Existing Base and Some Native Subgrade + Approx. 4% Lime	600,000	4 8 12 Avg.	0.47 0.43 0.39 0.40
Elkhart, Indiana County Road 3	Crushed AC + Existing Base Stabilized with SA-1 Stabilizer	140,000	4 8 12 Avg.	0.31 0.28 0.25 0.26
Flint, Michigan Interstate 69	Crushed AC + Existing Base Stabilized with Asphalt (used as Shoulders	116,000	4 8 12 Avg.	0.27 0.24 0.22 0.22

After reference 2.

Table 16. Structural Stiffness Ratios for Recycled Layers.

Project	Description of Layer	Reference Layer	Stiffness Ratio Recycled/Reference
11th Avenue, Hanford, California	Recycled Asphalt Road Mix Surface	Conventional Road Mix Surface	1.00
Russell Avenue, Fresno, California	Recycled Asphalt Stabilized Base	Conventional Road Mix Base	3.44
18th Avenue, LeMoore, California	Recycled Asphalt Stabilized Base	Conventional Aggregate Base	2.40
Highway 45, Yolo, California	Recycled Lime Stabilized Base	AC Surface	1.24
U. S. 56, Pawnee County, Kansas	Recycled Cement Stablized Base	AC (full depth)	1.12
U. S. 50, Dayton, Nevada	Recycled Cement Stabilized Base	AC Surface	0.42
U. S. 93, Wells, Nevada	Recycled Cement Stabilized Base	AC Surface	1.15
Ponderosa Avenue, Inclined Village, Nevada	Recycled Cement Stabilized Base	AC Surface	0.56

After reference 2.

Table 17. Costs of Common Recycling Operations - 1979.

Recycling Operation	Representative Cost Dollars - Per Square Yard - Inch*	
	Average	Range
Heat and Plane Pavement - 3/4 inch depth	0.30	0.15 - 0.60
Heat and Scarify Pavement - 3/4 inch depth	0.50	0.15 - 0.90
Cold Mill Pavement	0.85	0.30 - 1.25
Rip, Pulverize and Compact - Existing Pavement less than 5 inches of Asphalt Concrete	0.25	0.13 - 0.45
Rip, Pulverize, Stabilize and Compact - Existing Pavement less than 5 inches of Asphalt Concrete	0.45	0.20 - 0.50
Rip, Pulverize and Compact - Existing Pavement greater than 5 inches of Asphalt Concrete	0.30	0.15 - 0.50
Rip, Pulverize, Stabilize and Compact - Existing Pavement greater than 5 inches of Asphalt Concrete	0.50	0.25 - 0.60
Remove and Crush Portland Cement Concrete	0.60	0.30 - 0.90
Remove and Crush Asphalt Concrete	0.40	0.20 - 0.60
Cold Process - Remove, Crush, Place, Compact, Traffic Control - (Cold Process) without Stabilizer	0.50	0.30 - 0.75
Cold Process - Remove, Crush, Mix, Place Compact, Traffic Control - (Cold Process) with Stabilizer	0.60	0.35 - 0.90
Hot Process - Remove, Crush, Place, Compact, Traffic Control - without Stabilizer	0.75	0.45 - 1.20
Hot Process - Remove, Crush, Mix, Place, Compact, Traffic Control - with Stabilizer	0.90	0.50 - 1.25

*Costs are for a square yard inch except where listed.

1 yd = 8.361×10^{-1} m^2 1 in. = 2.54×10^{-2} m

After reference 2.

Table 18. Representative Costs for Pavement Recycling Operations - 1979.

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard		Assumptions
				Average	Range	
A. Surface	Heater Planer	Without additional aggregate	A1	0.60	0.45 - 1.15	Heat, plane, clean-up, haul, traffic control.
		With additional aggregate	A2	0.55	0.40 - 1.00	Spread aggregate, heat, roll, traffic control and clean-up.
	Heater Scarify	Heater scarify only	A3	0.60	0.35 - 1.00	Heat, scarify, recompact, traffic control (3/4 inch scarification).
		Heater scarify plus thin overlay of aggregate	A4	0.40	1.00 - 1.75	Heat, scarify, recompact, add 50 lbs. of asphalt concrete per square yard, compact, traffic control (3/4 inch scarification).
		Heater scarify plus thick overlay	A5	4.10	3.25 - 5.00	Heat, scarify, recompact, add 300 lbs. of asphalt concrete per square yard, compact, traffic control (3/4 inch scarification).
	Surface Milling or Grinding	Surface milling only	A6	0.75	0.45 - 1.50	Milling, cleaning, hauling, traffic control (1 inch removal).
		Surface milling plus thin overlay	A7	3.25	2.50 - 3.75	Milling, cleaning, hauling, 200 lbs of asphalt concrete, traffic control (1 inch removal).
		Surface milling plus thick overlay	A8	5.75	4.70 - 7.20	Milling, cleaning, hauling, 400 lbs. of asphalt concrete, traffic control (1 inch removal).

Table 18. Continued.

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard: Average	Range	Assumptions
B. In-Place	Asphalt Concrete Surface less than 5 inches	Minor structural improvement without new binder	B1	3.50	2.75 - 4.25	Rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	B2	3.00	2.40 - 3.70	Rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	B3	6.50	5.10 - 7.90	Rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	B4	5.10	4.10 - 6.20	Rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control.
	Asphalt Concrete Surface greater than 5 inches	Minor structural improvement without new binder	B5	3.75	3.00 - 4.50	Rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	B6	3.25	2.60 - 3.90	Rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	B7	6.90	5.50 - 8.25	Rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	B8	5.50	4.35 - 6.65	Rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control.

Table 18. Continued.

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard: Average	Range	Assumptions
C. Central Plant	Cold Mix Process	Minor structural improvement without new binder	C1	4.50	3.60 - 5.40	Remove, crush and replace to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	C2	3.75	3.00 - 4.50	Remove, crush, mix and replace to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	C3	8.00	6.40 - 9.70	Remove, crush and replace to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	C4	6.25	5.00 - 7.50	Remove, crush, mix and replace to 6 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement without new binder	C5	4.90	3.90 - 5.90	Remove, crush and replace to 4 inch depth with 1.5 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	C6	4.10	3.25 - 5.00	Remove, crush, mis and replace to 4 inch depth with 1/2 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	C7	8.25	6.60 - 9.90	Remove, crush and replace to 6 inch depth with 3 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	C8	6.50	5.25 - 7.75	Remove, crush, mix and replace to 6 inch depth with 1 inch of asphalt concrete.

After reference 2.

Table 19. Cost of Common Pavement Construction Operations - 1979.

Construction Operation	Representative Costs Dollars - Per Square Yard - Inch	
	Average	Range
Crushed Stone Base	0.60	0.30 - 0.75
Gravel Base	0.50	0.20 - 0.75
Lime Stabilized Subgrade	0.30	0.15 - 0.45
Cement Stabilized Subgrade	0.40	0.20 - 0.50
Cement Treated Base	1.00	0.60 - 1.40
Asphalt Treated Base	1.00	0.60 - 1.25
Lime--Fly Ash--Aggregate Base	0.90	0.60 - 1.00
Chip Seal	0.45*	0.20 - 0.55*
Asphalt Concrete	1.25	0.70 - 1.50
Portland Cement Concrete	1.65	1.00 - 2.50

*Price per square yard of surface.

1 $yd^2 = 8.361 \times 10^{-1}\ m^2$

1 in. $= 2.54 \times 10^{-2}$ m

Table 20. Cost of Pavement Rehabilitation Operations - 1979.

Rehabilitation Operation	Approximate Thickness, Inch	Representative Cost Dollars - Per Square Yard	
		Average	Range
Chip Seal Coat	1/2	0.45	0.20 - 0.55
Fabric Interlayers	1/4	1.10	0.75 - 1.75
Asphalt-Rubber Interlayer	1/2	1.25	0.90 - 1.50
Open Graded Friction Course	5/8	1.50	1.00 - 2.50
Asphalt Concrete (Dense Graded)	1	1.50	1.00 - 2.50
Asphalt Concrete (Dense Graded)	2	2.60	1.80 - 4.50
Asphalt Concrete (Dense Graded)	3	3.30	2.40 - 6.00

1 $yd^2 = 8.361 \times 10^{-1}\ m^2$

1 in. $= 2.54 \times 10^{-2}$ m

Table 21. Representative Energy Requirements for Pavement Recycling Operations.

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

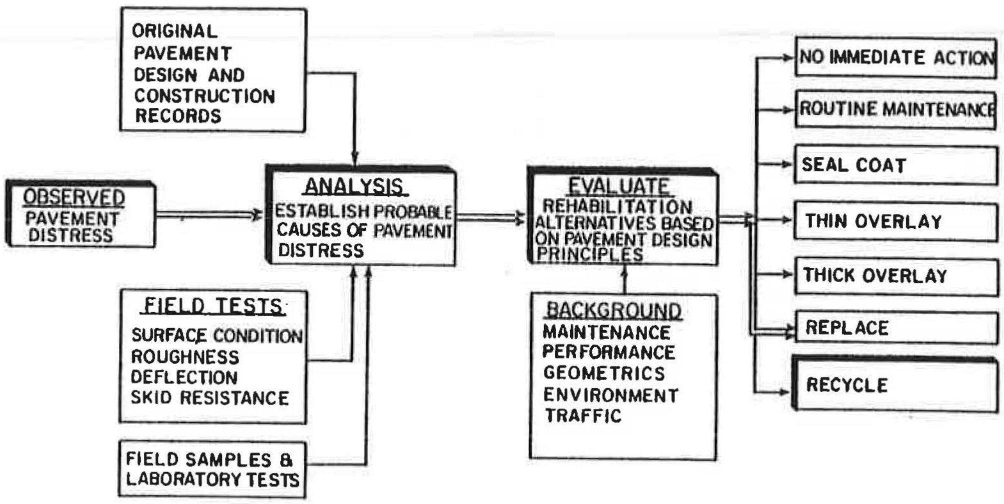
After Reference 2.

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

Table 22. Partial Listing of Cold Recycling Projects

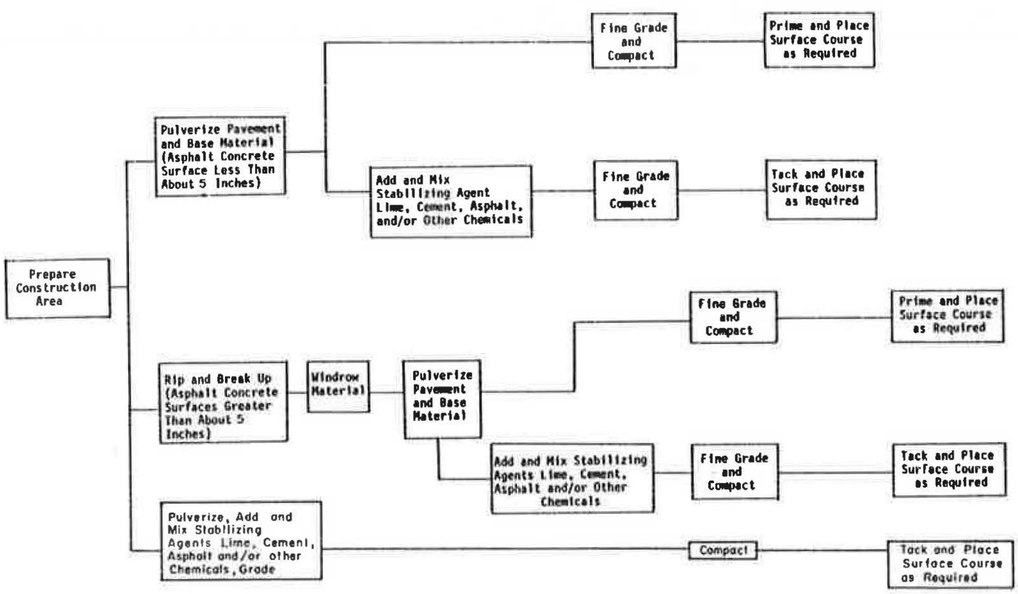
State	Recycled Material	Type of Agent	Reference
Alabama	Surface, Base	Cement	65
California	SubBase, Subgrade		2, 65, 71, 88, 92
Florida	Limerock Base		66
Illinois	Surface	Cement	65
Indiana	Surface, Base	None, Chemicals	83
Kansas	Surface, Base	Cement, Cutback, Emulsion, Bituminous Recycling Agent	2, 79, 82, 91
Louisiana	Surface, Base	Cement	91
Maine	Surface, Base		73, 74, 77, 86
Massachusetts	Surface, Base		75
Michigan	Surface and Base		67, 68, 71, 81, 89, 90
Misssouri	Surface, Base	Emulsion	87
Nevada	Surface and Base		2, 69, 91
New Mexico	Surface, Base	Cement	91
North Dakota	Surface	None	65
Texas	Surface		70, 76, 78, 80
Utah	Surface	Cement	65
Vermont	Surface, Base	Emulsion	85
Virginia	Surface, Base	Cement	65
Wisconsin	Surface, Base	None, Cement, Emulsion, Chemicals	84, 91
FHWA	Surface, Base	None, Emulsion, Chemical	65

Figure 1. Recycling as a rehabilitation alternative.



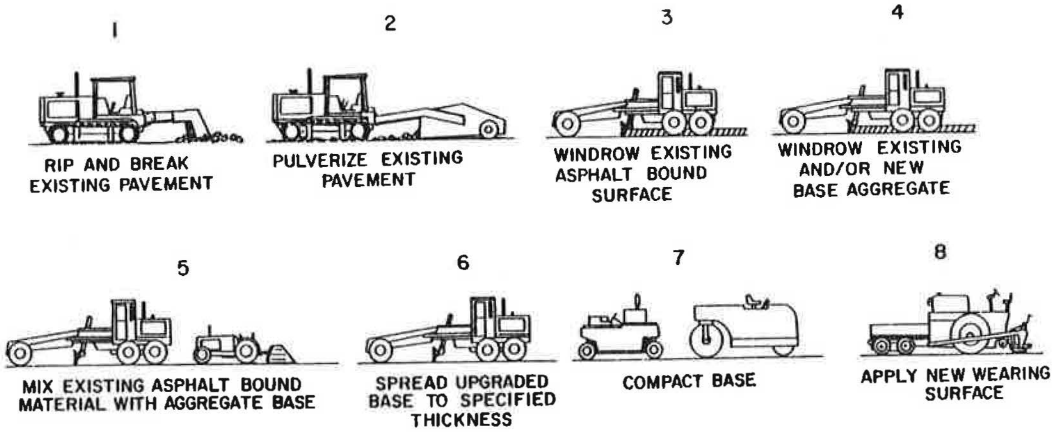
After reference 2.

Figure 2. Cold In-Place Surface and Base Recycling.



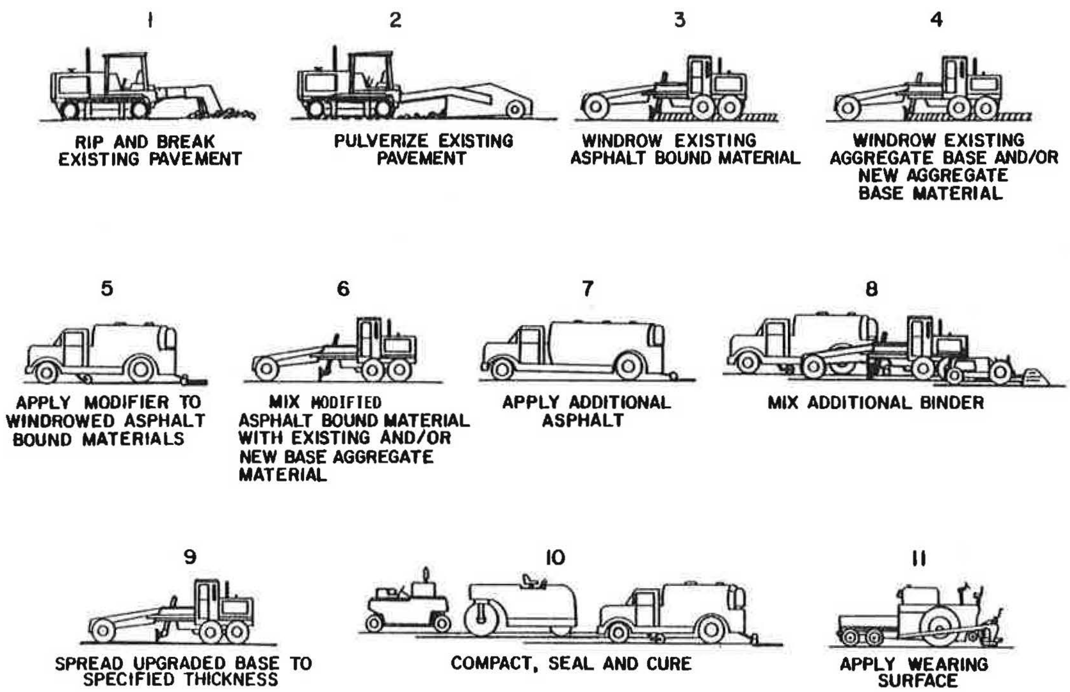
After reference 2.

Figure 3. Typical Cold In-Place Recycling Operation Without Restabilization.



After reference 2.

Figure 4. Typical Cold In-Place Recycling Operation with Modifier Agent and Additional Binder.



After reference 2.

Figure 5. Cold Central Plant Surface and Base Recycling.

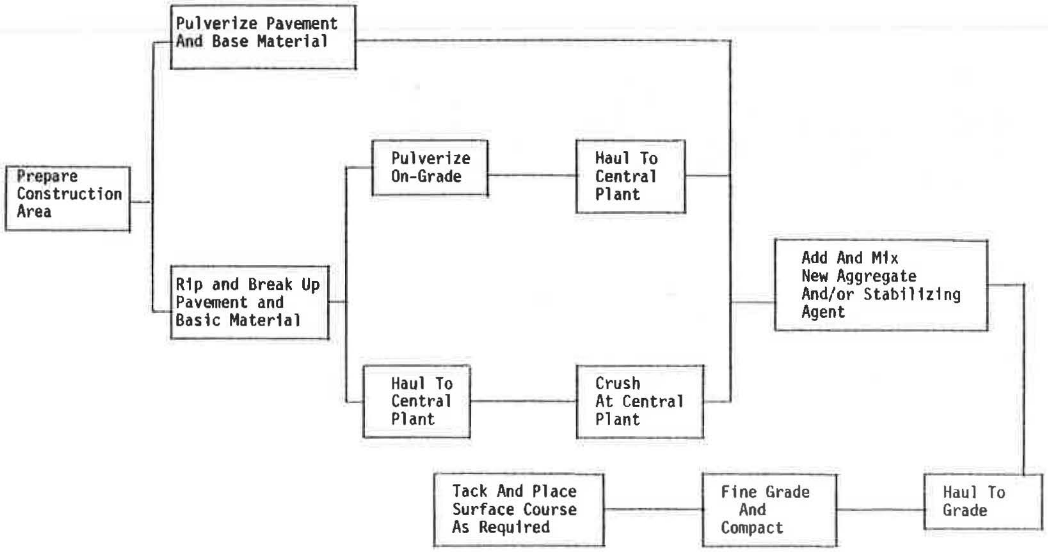
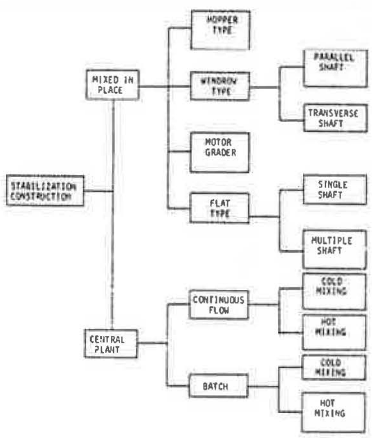
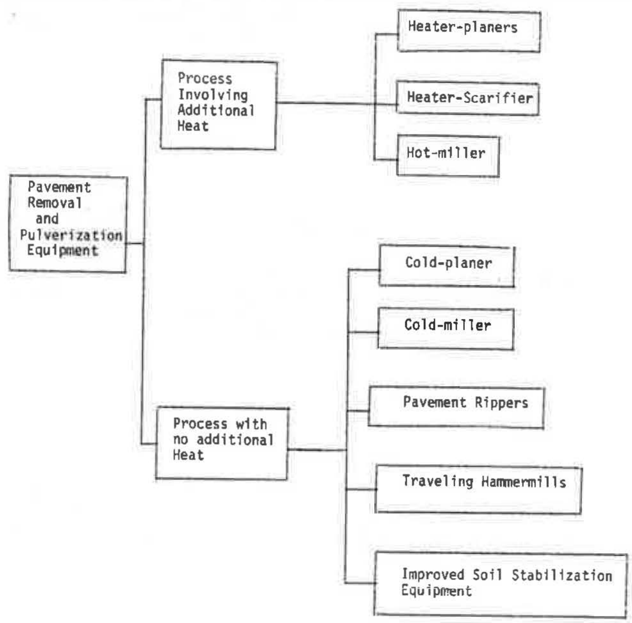


Figure 6. Soil Stabilization construction equipment.



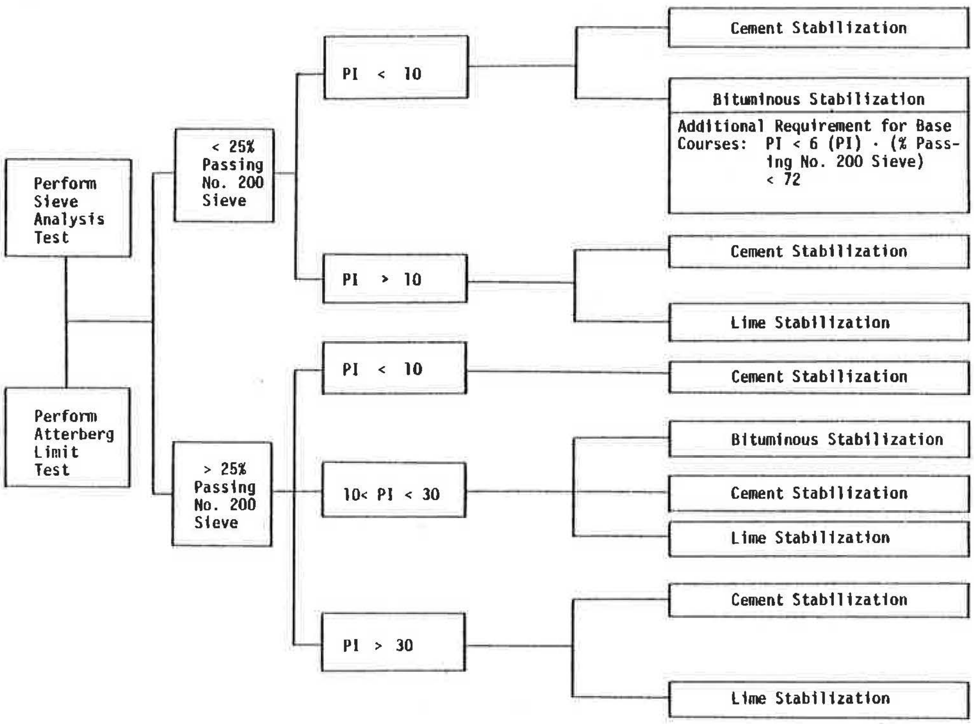
After reference 24.

Figure 7. Pavement Removal and Pulverization Equipment Associated with Cold Recycling Operations



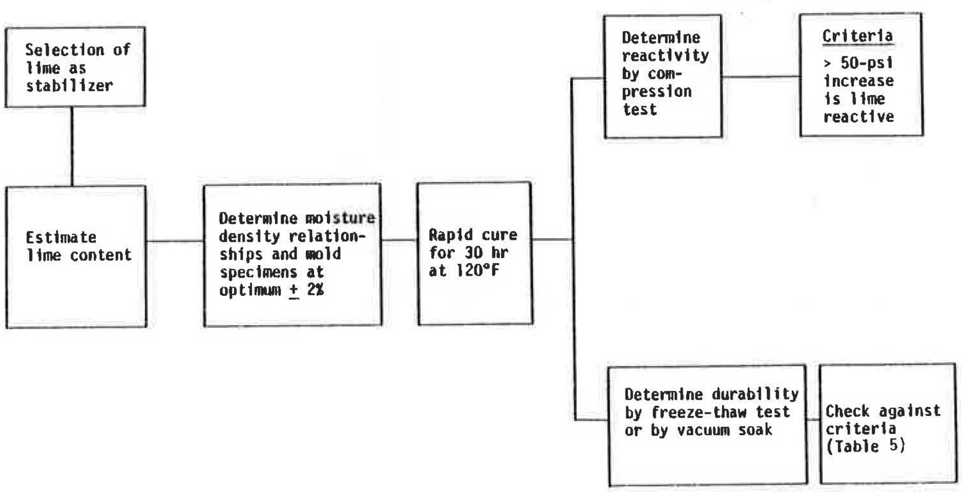
After reference 1.

Figure 8. Selection of Stabilizer.



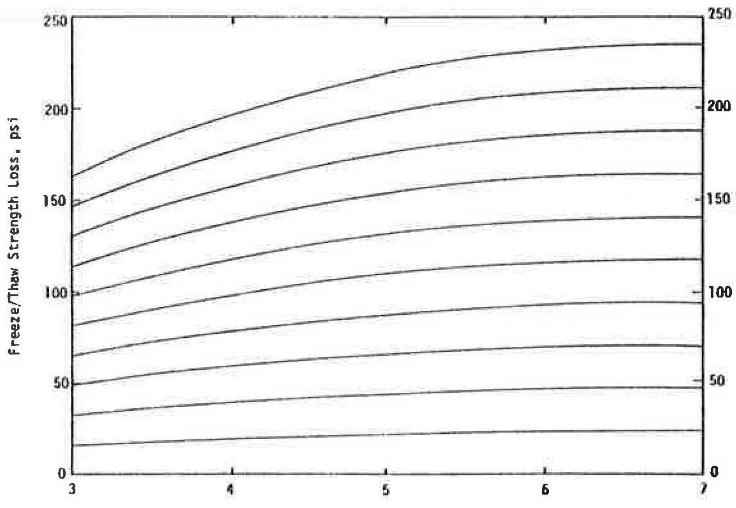
After reference 33.

Figure 9. Design Subsystem for Stabilization with Lime.



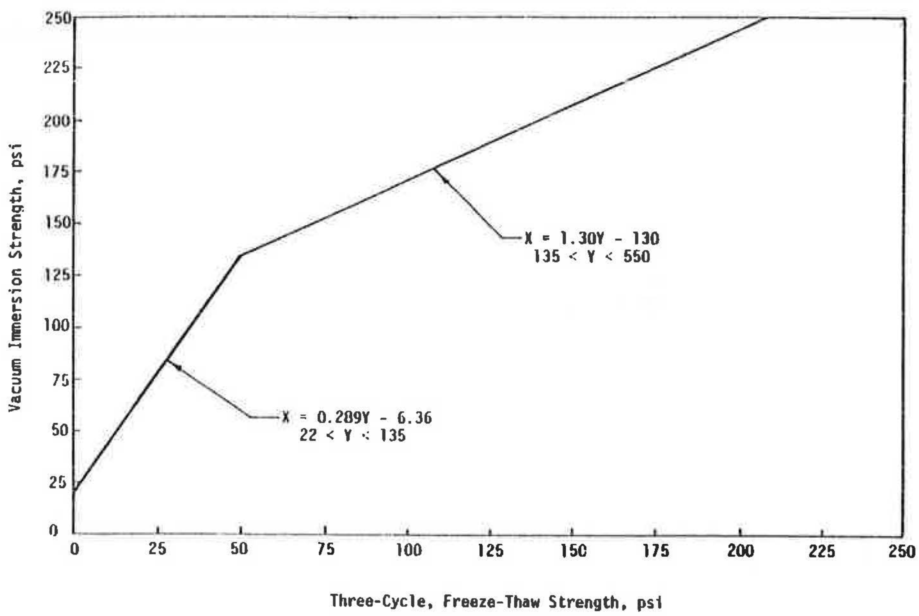
After reference 39.

Figure 10. Design Chart for Freeze-Thaw Loss.



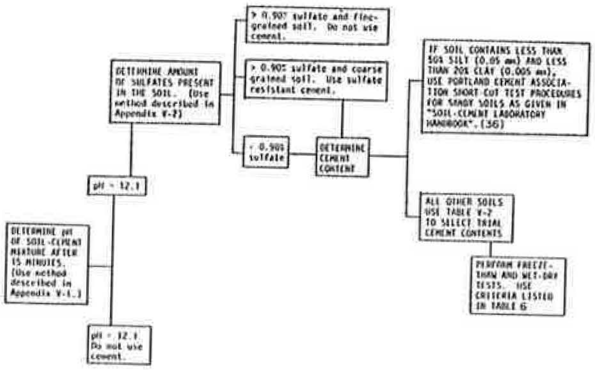
After reference 39.

Figure 11. Design Chart for Three-Cycle, Freeze-Thaw Strength from Vacuum Immersion Strength.



After reference 34.

Figure 12. Design Subsystem for Stabilization with Portland Cement.



After reference 24.

Figure 13. Mixture design procedure.

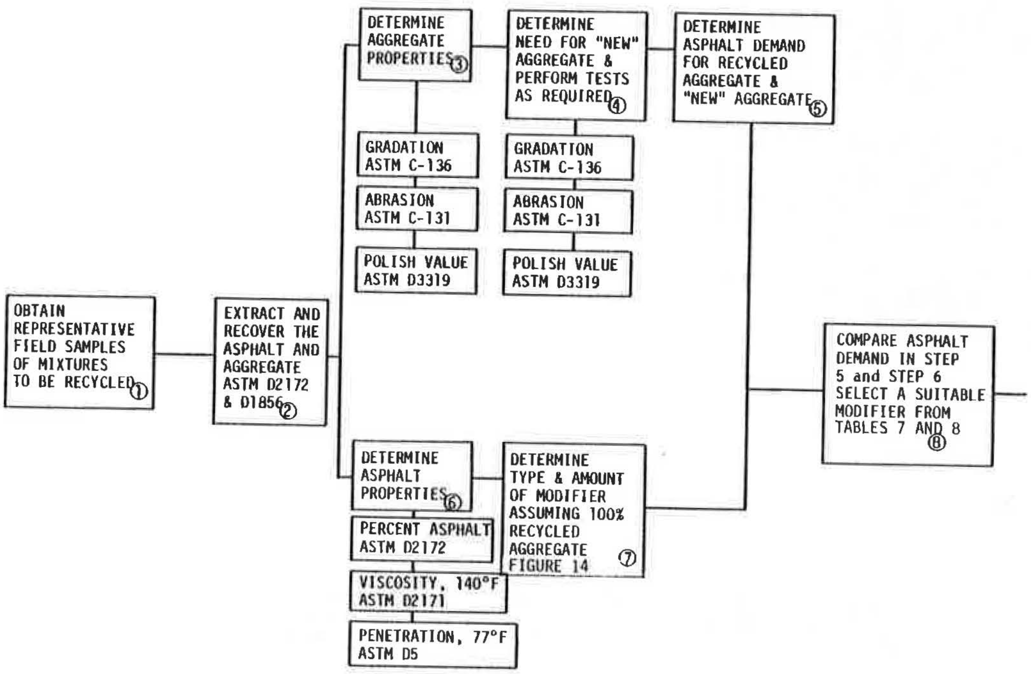


Figure 13. Continued

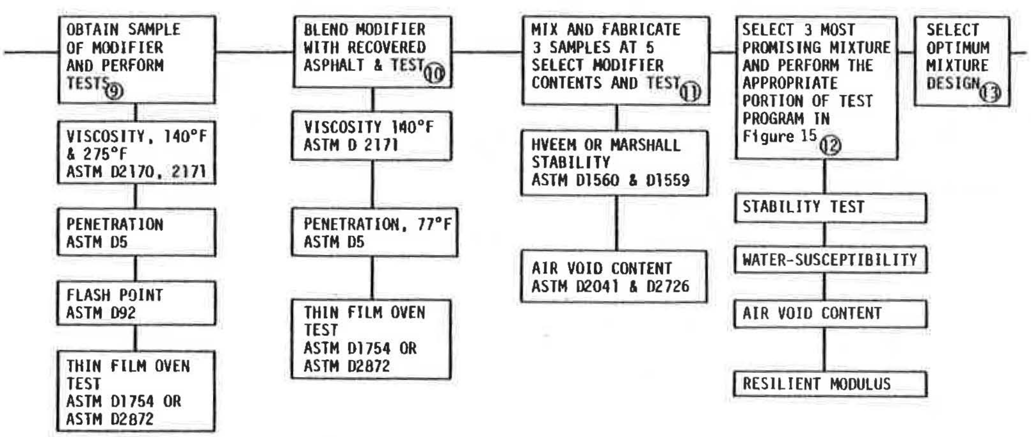
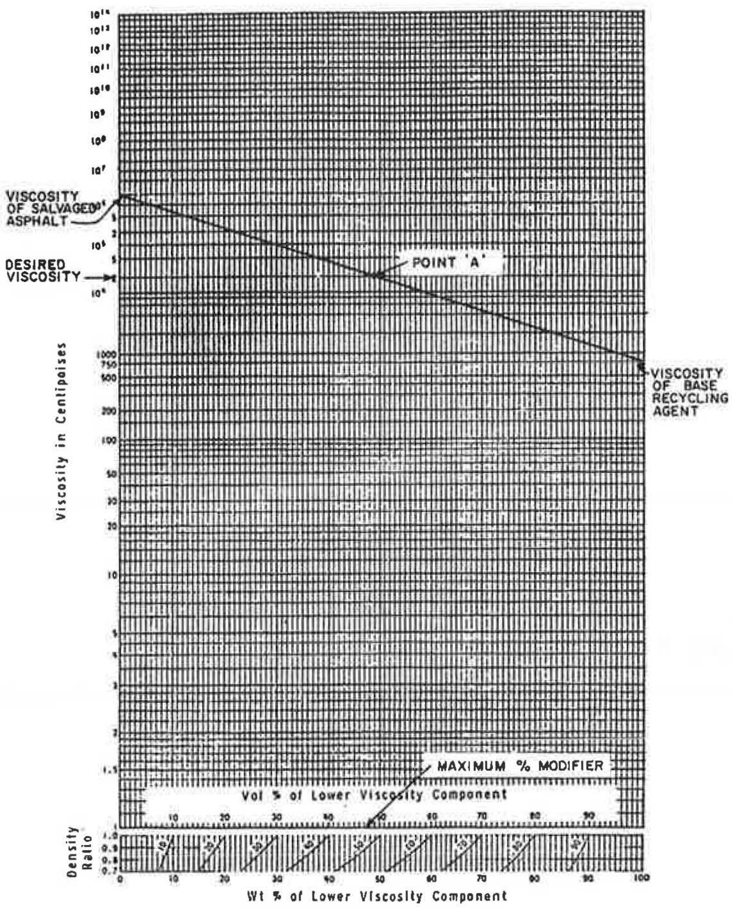


Figure 14. Viscosity Blending Chart.



After reference 39.

Figure 15. Test Sequence for Mixture Evaluation.

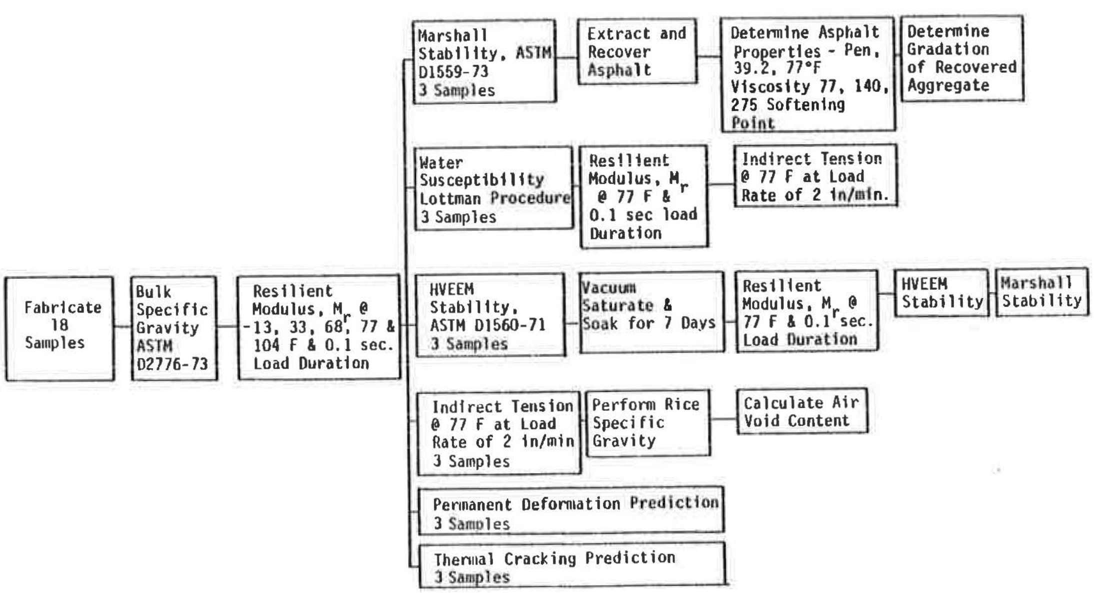
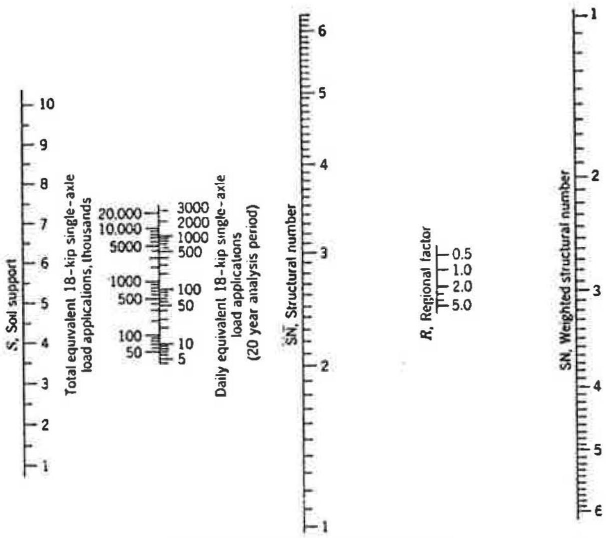
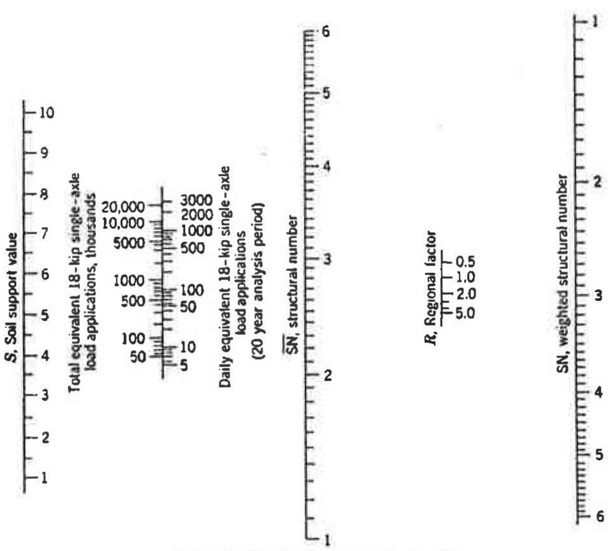


Figure 16. AASHO flexible-pavement design nomographs.



Design chart for flexible payments, $P_t = 2.0$



Design chart for flexible pavements, $P_t = 2.5$

After reference 50.

Figure 17a. Soil support value correlations, (a) after Utah State Highway Department and (b) from reference 57.

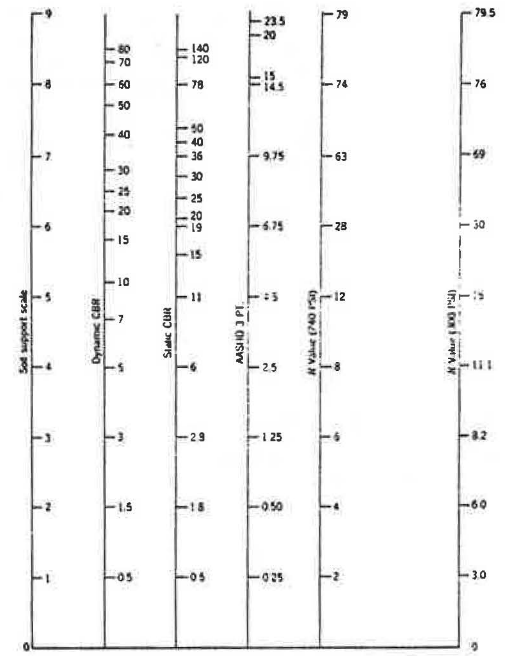


Figure 17b. Continued.

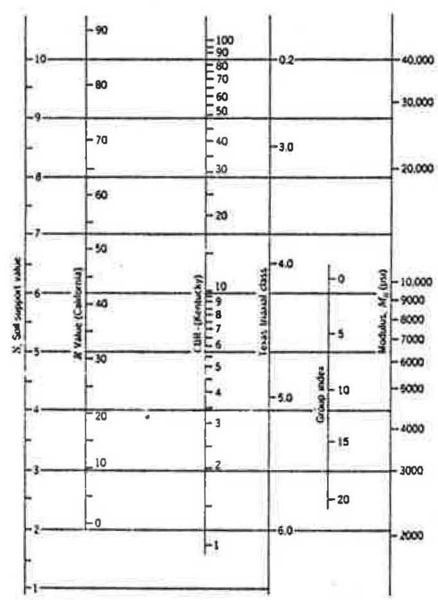
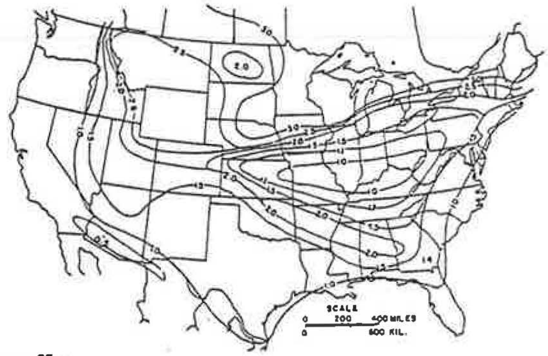
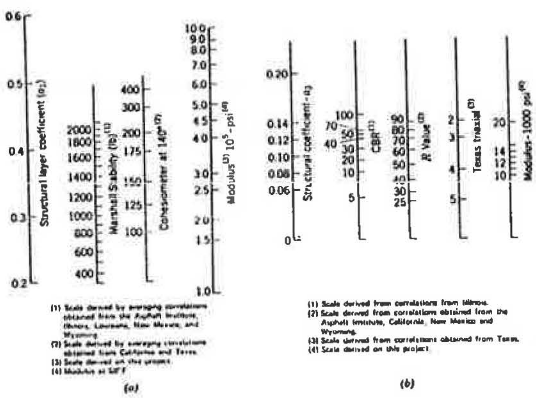


Figure 18. Generalized regional map of the United States.



After reference 57.

Figure 19. Suggested AASHO layer coefficient nomographs. (a) variation in a_1 with surface course strength parameters; (b) variation in a_2 for granular subbase and subbase strength parameters; (c) variation in a_2 for bituminous-treated bases with base strength parameters; (d) variation in granular coefficient a_2 with base strength parameters in a_2 for cement-treated base with base strength parameters.



After reference 57.

Figure 19. Continued

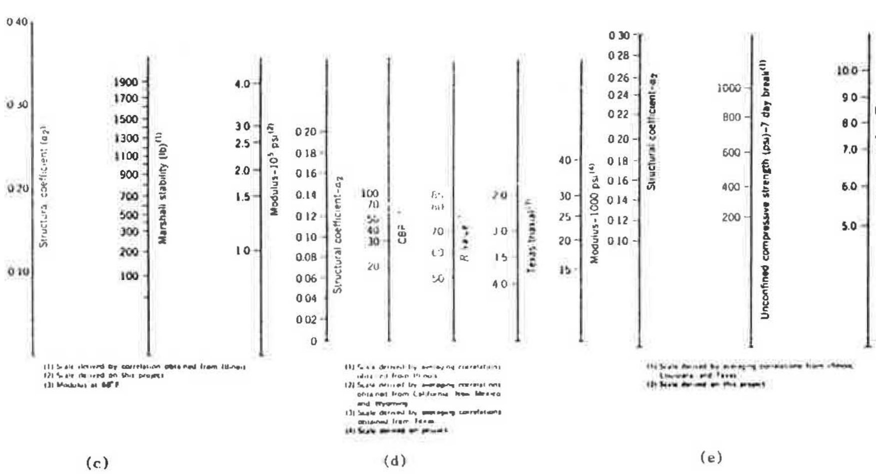
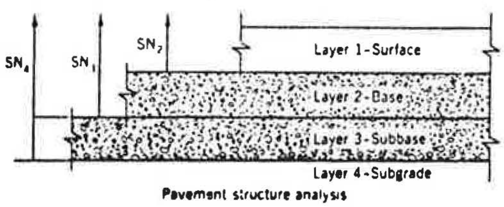
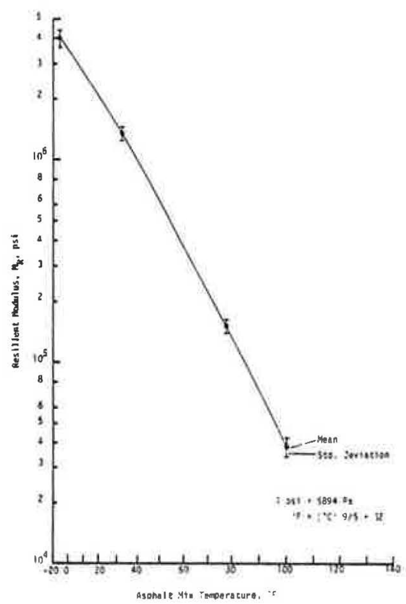


Figure 20. Alternate procedure for determining flexible-pavement layer thicknesses.



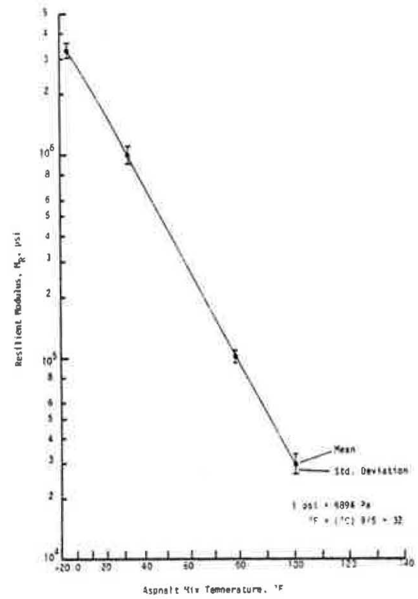
After reference 57.

Figure 21. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 56, Kansas - Section 1. (Recycled asphalt Concrete with 20% cement).



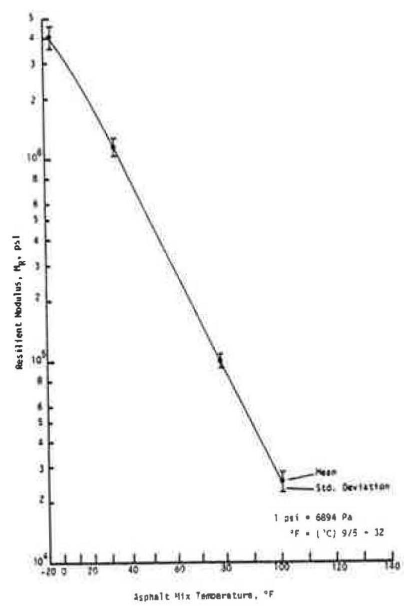
After reference 2.

Figure 22. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 56, Kansas - Section 2. (Recycled Asphalt Concrete with 1.5% cement).



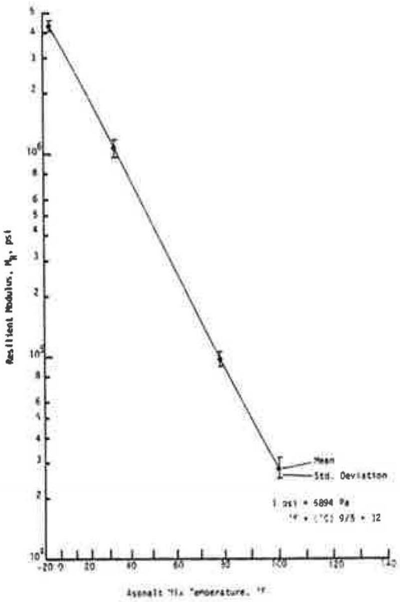
After reference 2.

Figure 23. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 56, Kansas - Section 3. (Recycled Asphalt Concrete with 1% MC-8VV).



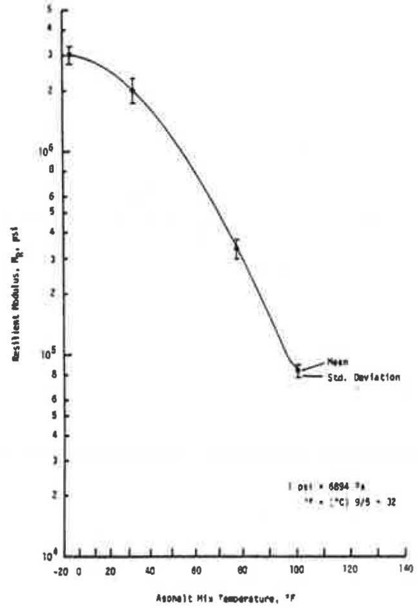
After reference 2.

Figure 24. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 56, Kansas - Section 4. (Recycled Asphalt Concrete with 1.5%. Cement and 1.5% AC-7).



After reference 2.

Figure 25. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 277, Abilene, Texas. (Recycled Asphalt concrete with Emulsified Recycling Agent).



After reference 1.

COLD - ASPHALT RECYCLING EQUIPMENT

John F. Wood, Midwest Asphalt Paving Corporation

Following is a general outlook on the history and development of construction equipment for use in the cold-asphalt recycling process:

Mixed in place road construction was first introduced in the United States about 1980, in Southern California. In most cases, standard farm equipment was used. Disk harrows, tow blades and drags mixed the liquid road oil into the road bed. The distribution of the liquid road oil was very poor at that time. With the introduction of liquid distributors around 1920 and SC (slow curing liquid asphalt) around 1925, road mix (mixed-in-place) finally became a widely used procedure in the farm to market type road construction.

Specialized equipment for mixed-in-place (now called cold-in-place recycling) was first developed in 1926 by the Barber-Green Company. Other companies that made stabilization equipment at about the same time were; Iowa Manufacturing, Madsen Manufacturing, Woods (now Pettibone) and Jager Machine Company. All of the aforementioned machines were developed to eliminate the use of liquid distributors for the distribution of liquid asphalt. Construction equipment designing for use in the cold-in-place recycling process is continuing at the present time.

In-Place Equipment

In-Place Crushers

Grid Rollers. Grid rollers in conjunction with grader and scarifiers were first used to breakup existing road beds about 1928 to 1930. The grid roller was made of steel rebar interwoven to a 4" opening. Others were made with smaller openings down to a 2" opening.

Other types of grid or impact crushers are made by Ateco and Gemco. They attach to a motor grader and after the road is scarified, the impact crusher is used by applying down pressure from the grader and the foreward speed causes the material to break down. They are mostly used on seal coat roads, or as a pre-crusher for use with a Hammer-mill.

Hammer-mills. Hammer-mills were introduced in the late 1940's by The Brother's Company. They were originally designed as rock crushers to build roads in the heavy rock country of Montana and other mountainous regions. When used in the recycling process, the road bed must first be scarified and placed in a windrow prior to being crushed. The grid in the rear of the machine determines the size of the crushed material. Hammer-mills are still being produced at the present time by Pettibone Company.

Rotary Reduction Machines. The following is the definition of crushing equipment for in-place cold recycling from the Michigan DOT: "When the use of crushing equipment is specified in the proposal, the equipment shall be an approved rotary reduction machine having positive depth control adjustments in increments of one-half inch and capable of reducing material which is at least six inches in thickness. The machine shall be of a type designed by the manufacturer specifically for reduction in size of pavement material, in place, and be capable of reducing the pavement material to the specified size. The cutting drums shall be enclosed and shall be enclosed and shall have a sprinkling system around the reduction chamber for pollution control. The rate of forward speed must be positively controlled in order to ensure consistent size of reduced material. The machine must be equipped with an accurate tachometer which is mounted in full view of the operator. The crushing equipment shall meet the approval of the Engineer." (1.)

Several of the machines presently being produced are Barber-Green, CMI, Barco, Rancho, and several foreign machines.

Advantages and Disadvantages. Advantages and disadvantages of the above machines are as follows: The grid or impact roller, although suitable for tearing up and crushing of seal coat and oil agg roads, is too time consuming to be profitable in crushing of plant mixed roads.

Hammer-mills are very well suited for the crushing of plant-mixed roads, except when the asphalt is in excess of four inches. The problem then becomes not the crushing, but the scarification of the thicker asphalt and the placing of this material in a windrow suitable for the hammer-mill to crush.

Most Rotary Reduction or Cold Milling machines on the market are suitable for reducing all types of asphalt roads and to most any depth. They also have the advantage of not disturbing the underlying base and traffic disruption is minimal. The one disadvantage to these machines is that their cost of operation does not make it feasable to use on seal coat or thin 3/4" to 1½" of plant-mixed asphalt.

The decision on what type of equipment to be used in cold-in-place recycling should not be specified as to type but rather to an end result spec, such as 1", 2" or 3" maximum size and a percent of over size such as 95% to pass a 2" screen, etc. This end result type specification then becomes the responsibility of the contractor and the type of equipment and the amount of time that he must spend meeting that spec will determine the type, size, and number of equipment pieces he will use.

Single Rotor Stabilizers

Clockwise Rotation. Clockwise ratation machines are made by several companies such as, Rex, Seman, Brothers & Kohering and Pettibone. Most of the machines use an L type tine or mixing tooth. All of these can be adapted to cold-in-place recycling by addition of tacometer wheels to give the operator a Ft/Min reading and an asphalt pump and meter with a Gal/Min meter, therefore, with Ft/Min width of machine and depth of cut, Gal/Min can be easily determined to give the proper percent of liquid asphalt.

Counter Clockwise Rotation. Counter clockwise machines are produced by Raygo-Kohering & Bros. All machines have the same ability as the above to be adapted for cold-in-place recycling with the addition of tac wheel and pump and meter.

Advantages and Disadvantages. The advantages of the down cut (Clockwise) is that the material being mixed remains in the mixing chamber for a longer period of time. The disadvantage of the down cut is the amount of power required to down cut.

The Counter Clockwise machines has less down time for maintenance as the up cut requires less effort.

Multi Rotor Stabilizers

Advantages and Disadvantages. The P & H was sold to Kohering in 1957 and the single pass multirotor machine was produced until 1962 or 1963. There are many of these machines still in use today. With the multirotor machine you are able to cold-in-place recycle using penetration grade asphalt cement, with production rates of two full width road miles per day.

The big disadvantage of the machine is it's age and most replacement parts must be made special order.

Traveling Pugmills

Advantages and Disadvantages. Midland machinery produces a self-contained traveling pugmill that includes; asphalt tank, conveyor for loading material and a twin shaft pugmill that discharges the mixed material to an asphalt screed to leave a finished surface.

Pettibone also makes a traveling pugmill that picks up a sized windrow and deposits the material in a windrow behind the machine to be laid out with a grader.

Both of the above machines produce a quality product because the material to be mixed is removed from the grade and therefore the metered material (asphalt and gravel) are proportioned to a predetermined mix design.

The disadvantage is the production per day is less than one mile.

Future Design

Needed Improvements. The future design needed to meet all requirements for cold-in-place recycling would be a machine that would crush the existing road material, (i.e. Seal Coat, road mix, or hot plant-mixed asphalt) remove the material from the grade, meter this material and meter the addition of additional binder, then pave with this material to the proper grade and cross section. The machine should also be capable of changing width where and when needed, such as a screed extention on most conventional asphalt pavers.

Plant

Many companies are using conventional stationary crushers and asphalt plants as well as portable crushers and mixers, however, the cost of removal and replacement of materials from the road bed are very expensive and therefore, impractical. I make this statement with reservation, because for small jobs, it would not be practical for a contractor to invest in cold-in-place recycling equipment when he had stationary equipment suitable to do the job.

1. Michigan Department of Transportation. 1979 Standard Specifications for Construction. Division 4, Section 4.07, b., pg. 171.

URBAN COLD RECYCLING

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ABSTRACT: Following is a general discussion of the basic procedures for asphalt pavement recycling covering (a) preparatory steps required, (b) description of a proper recycling agent, and (c) important steps in cold recycling affecting the mechanics of field procedures. It includes a description of two recent cold recycling projects performed in California, and a comparison of energy requirements for new construction with four different recycling procedures.

The subject assigned to me for discussion is "Urban Cold Recycling." The work to be performed on urban and rural roads is somewhat different because of differences in grade control, obstruction, traffic, access to adjacent property and other factors. However, contractors have moved from urban to rural, from congested to desolate areas, and from complicated to very simple projects with ease and hardly a ripple. Therefore, there should be no problems in adapting to recycling techniques, either rural or urban.

This paper presents an overall picture of the procedures followed on two typical cold recycling projects recently completed, one by the City of Victorville, California, and the other a Kern County, California project. The Victorville project involved breaking up and removing the asphalt concrete pavement to adjacent empty lots to allow correction of base problems, and hauling the crushed material back to the road to be mixed and laid. The Kern County project involved breaking up the existing asphalt concrete pavement, mixing and laying without moving it off the site. This was done within a 12 foot lane width with a concrete curb on one side and a concrete traveling lane on the other side. In other words, it was accomplished in a confined and controlled grade set-up similar to any city street.

Before going into the details of these two projects, I believe it appropriate to discuss briefly some facts and aspects basic to recycling and recycling agents in general.

There are three characteristics of any pavement to be recycled which must be known before the design engineer can develop the final mix formula. This is true for any pavement regardless of what recycling procedure is contemplated -- hot, cold, on- or off-site, 100% recycled pavement or a blend of recycled pavement and new aggregate. The three facts to be determined in the laboratory are:

1) Percent of residual asphalt in the existing pavement;
2) Consistency of the residual asphalt (penetration value or viscosity); and
3) Asphalt demand of the recycled aggregate.

With this information, the design engineer can determine amount and type of recycling agent required to achieve a final mix of the quality desired by the agency in charge.

After the laboratory investigation of the pavement to be recycled is completed and the design engineer has the necessary information to develop the final mix, the next step is to make certain that a properly formulated recycling agent is specified as the additive. This recycling agent must have characteristics which will result in a final mix exhibiting workability, stability and durability. Workability and stability can be achieved with many available additives; however, durability is by far a more difficult achievement. But it must be fulfilled. There is no point in going to all the trouble, effort and cost to recycle a pavement if durability is not achieved. This can be assured by the simple expediency of setting up meaningful material specifications with the proper limits for specific properties. The properties that must be specified in all specifications of general validity are: viscosity, flash point, weight change, saturates, compatability with residual asphalt as measured by the ratio N/P, aging ratio and specific gravity. We at Golden Bear have gone even further and included in our quality control specification tests, volatility and all values for chemical composition.

The emulsified versions of our commercial recycling agents must be made of the approved base oils and in addition must comply with set requirements for the emulsion including pumping stability and stability in the cement mixing test, must contain a minimum of 60% residual oil, and must be cationic. Tables 1 and 2 show our own laboratory acceptance specifications for recycling agents

Table 1. Specifications for Cyclogen Recycling Agents.

Property	Test Method	L[a]	M[a]	H[a]	22[a]	47[a]
Viscosity @ 140 F, cSt	ASTM D 2170-74	200-800	1000-4000	5000-10000	15000-35000	40000-60000
Flash Point, COC, F	ASTM D 92-72	400 min.	450 min.	450 min.	475 min.	500 min.
Volatility, IBP, F	ASTM D1160-61, 10	300 min.	325 min.	350 min.	--	--
2%, F		375 min.	400 min.	425 min.	475 min.	475 min.
5%, F		410 min.	430 min.	440 min.	500 min.	500 min.
RTFC weight change, %	ASTM D 2872-74	4.0 max.	2.0 max.	2.0 max.	0.5 max.	0.5 max
Compatibility, N/P	ASTM D 2006-70	0.5 min.	0.5 min.	0.5 min.	--	--
Saturates, % W	ASTM D 2007-75	28 max.	28 max.	28 max.	28 max.	28 max.
Chemical Composition $(N+A_1)/(P+A_2)$	ASTM D 2006-70	0.2 - 1.2	0.2 - 1.2	0.2 - 1.2	--	--
RTFC Ratio[b]	ASTM D 2872-74	2.5 max.	2.5 max.	2.5 max.	2.5 max.	2.5 max.
Specific Gravity[c]	ASTM D 70-72	0.98 - 1.02	0.98 - 1.02	0.98 - 1.02	0.98 - 1.02	0.98 - 1.02

[a]Suitable pumping temperatures are the following: L=140 F, M=190 F, H=200 F, 22=230 F, and 47=250 F

[b]Viscosity, RTFC Residue @ 140 F cSt/Viscosity, Original Material @ 140 F, cSt

[c]For conversion of the L, M & H Series use 242 gal./ton; for 22 & 47 use 238 gal./ton

Table 2. Specifications for Emulsified Cyclogen Recycling Agents, LE[a], ME[a], HE[a]

PROPERTY	TEST METHOD	SPECIFICATIONS
Viscosity @ 77 F, SFS	ASTM D 244-76	15-85
Pumping stability	G.B. method[b]	Pass
Emulsion coarseness, percent	Sieve Test ASTM D 244-76 (MOD)[c]	0.1 max.
Sensitivity to fines, percent	Cement Mixing ASTM D 244-76	2.0 max.
Particle charge	ASTM D 244-76	Positive
Concentration of oil phase, percent	ASTM D 244-76 (MOD)[d]	60 min.

Note: CYCLOGEN 22 and 47 are not furnished as an emulsion.

[a]Oils used for emulsions must meet specifications for the CYCLOGEN recycling agents L, M, H. For the conversion of LE, ME and HE use 242 gal./ton.

[b]Pumping stability is determined by charging -450 ml of emulsion into a one-liter beaker and circulating the emulsion through a gear pump (Roper 29 B2262) having ¼" inlet and outlet. The emulsion passes if there is no significant oil separation after circulating ten minutes.

[c]Test procedure identical with ASTM D 244 except that distilled water shall be used in place of two percent sodium oleate solution.

[d]ASTM D-244 Evaporation Test for percent of residue is modified by heating 50 gram sample to 300 F until foaming ceases, then cooling immediately and calculating results.

Table 3. Calculation of Asphalt Demand of Recovered Aggregate

$$P = \frac{4R + 7S + 12F}{100} \times 1.1$$

P = Total % asphalt required in recycled mix (old asphalt + recycling agent)

R = Rock (retained on #8 sieve)

S = Sand (passing #8 sieve; retained on #200)

F = Fines (passing #200 sieve)

(base oils and emulsified grades) which we manufacture and which, by our tests, will fulfill all the necessary and needed requirements to achieve workability, stability and durability.

To go into further detail on the chemistry of recycling agents would be outside the scope of this paper. For those interested in some of the details, I refer you to two review papers I presented recently on the chemical aspects of pavement recycling affecting engineering considerations: (1) a prepared discussion for the Symposium on Recycling of Asphalt Mixtures, published in the Proceedings of the Association of Asphalt Paving Technologists, Vol. 43, pp. 327-339, 1979, and (2) "Rejuvenating Materials," presented at the Conference on Recycling of Asphalt Pavements, University of Michigan, March 25-26, 1980. These two papers describe the asphalt chemistry as practiced by Golden Bear, in language easily understood by engineers as well as chemists.

It would be well to mention at this time the fallacy of specifying high penetration asphalts or asphalt emulsions as the sole additive for any recycling project. Although a high penetration asphalt contains all the components specified in a recycling agent, if the ratio of the components is uncontrolled, the composition of the cement in the final mix is unknown and end results are unpredictable. Recycling is a costly procedure. To consider workability only and ignore durability is wrong. Why gamble and waste all the effort, energy, money and time for what will in practically all cases be a pavement of questionable durability? Those who advocate using high penetration asphalts for recycling are in essence advocating a mix design which, in most cases, will contain a binder which might result in a pavement of impressive appearance when freshly laid, but which is a gamble as to future performance.

To return to the subject of actual field construction of urban cold recycling, I want to present to you now the pertinent facts of the City of Victorville and Kern County projects.

City of Victorville

For the City of Victorville, estimated savings of approximately $100,000 by cold recycling of residential streets was the main incentive. The existing pavement was 2½" thick and the design requirements in this area, due to soil conditions and traffic requirements, called for four inches of pavement. If the old time-honored procedure of removing and disposing of the existing pavement and replacing it with four inches of new pavement were to be followed, Victorville could not afford to proceed with the project.

A representative sample of the asphalt pavement was analyzed showing an asphalt content of 5.4% with a penetration value of 7 and a viscosity of 653,000 poises. The asphalt demand of the aggregate was 6.3%. This was arrived at by using the surface area formula shown in Table 3. This asphalt demand called for an addition of approximately 1% of a recycling agent. Since this was to be a cold recycling project, the emulsion form of the recycling agent was required. The emulsion contained 60% residual, meaning that the total amount of emulsion needed was 1.7% by weight. The recycling agent used by the contractor was CYCLOGEN LE, a one-component material developed, manufactured and supplied by Golden Bear Division-Witco. The specifications also required the old asphalt pavement to be broken up so that 100% would pass the 1½" sieve, 90-100% would pass the 1" sieve and 0-8% would pass the No. 200 sieve. Since base repair had to be performed, the old crushed pavement was stored in empty lots adjacent to the project. When the base work was completed, the old pavement was hauled back to the roadway, dumped into the hopper of a Midland mixer-paver. The Midland mixer-paver had the capability of introducing the CYCLOGEN LE into the mix at the predetermined rate, mixing and laying the 2½" depth 12 feet wide in one pass. Compaction followed with a vibrating roller. The street was opened immediately to traffic and received the final 1½" of new asphalt mix several days later.

The City of Victorville plans more cold on-grade recycling work; however, the final riding surface will be a slurry seal, which should be adequate under most conditions prevailing on residential streets.

Kern County Project

In the Kern County project, all preliminary work was the same as in the Victorville jobs, but the field procedure was slightly different. There was no base problem to correct. The total thickness of pavement was four inches. The specifications called for recycling the top three inches, leaving 1" undisturbed. Using a milling machine, the old pavement was broken up on the grade to the same gradation requirements as in Victorville. The crushed material was left on the roadbed and windrowed. A Midland mixer-paver with a Ko-Call on the front then moved down the grade, picking up, mixing and laying to grade in one pass. The recycling agent used on this project was again CYCLOGEN LE, supplied by Golden Bear, and was introduced into this mix at a rate of 2.7% by weight. This project is scheduled to have a chip seal as its final riding surface.

General Observations

Having been personally involved in many cold recycling projects, I believe I should mention several items regarding the actual mechanics and procedures that one must make sure are followed. The pavements must be crushed or milled so that 100% passes the 1½" sieve. This is necessary to assure a reasonable gradation, proper mixing and compaction. Oversize material can be detrimental to these requirements. It is advisable to use the amount of recycling agent calculated for the mix regardless of what the immediate visual appearance may be. It must be kept in mind that the recycling agent needs a certain amount of time to react completely with the residual asphalt, but the ability of the recycled mix to perform and function is in no way inhibited during this reaction time. Traffic should be allowed to use the facility as soon as possible after compaction. It is also usually required that some type of seal, such as conventional asphalt emulsion or rejuvenating agent be sprayed on the recycled mat prior to placing the final riding surface. The reason for the seal is that most cold recycling projects end up with voids in the area of 6%, and it is well to seal them off from the intrusion of air and water.

Features unique to urban projects are the obstructions, such as curbs, gutters, manhole covers, valves and other utility features which must be protected from damage and meet the final grade. Small, maneuverable milling equipment is available to grind around obstructions or in small areas so all the old pavement can be utilized. If it is impractical or impossible to recover material from small, inaccessible areas, it can be removed and hauled off to a central stockpile for further use. In other words, recycling can be performed economically and expeditiously regardless of the locality or conditions.

For recycling where a given grade must be maintained but traffic and soil conditions indicate need for additional thickness of pavement or strengthening the base, the following procedure may, and in most cases will, fulfill the structural requirements. In this case, the procedure would be to grind up the existing pavement and windrow it off to the side or stockpile it off the site. Using a standard asphalt emulsion, a black base can then be made of the existing material to the necessary thickness to meet the structural requirements. However, this can be done only if the existing base material meets requirements, such as a reasonable gradation and proper sand equivalent so that it can be converted from an untreated rock base to an asphalt treated base. This will allow the design engineer to assign a greater gravel equivalent thickness to the existing untreated base and will generally be sufficient to satisfy the structural thickness requirements in residential, secondary or collector streets, without removing or hauling base material.

There are those who advocate mixing the existing base with the crushed pavement for the recycling procedure. This should be considered only if the thickness of the pavement is less than two inches. Then the mixture of crushed pavement and base should be treated and mixed on the same basis as an untreated base due to the insignificant amount of residual asphalt. If the pavement is at least two inches thick and the structural design calls for additional overlay or load carrying capacity, the base should be separated from the surface and the two mixed separately.

There are also other advantages to cold recycling which are of utmost importance. No serious air pollution problems are involved, and there is a considerable savings in energy which in turn translates to a savings in money.

To point out the savings in energy, I want to give a brief review of a specific project setting forth the energy requirements for five different approaches - four recycling procedures and one procedure replacing the road with all new materials. The project comprises a three-mile long asphalt pavement, 24 feet wide, four inches thick. The plant where all off-site work (hot or cold) is to be performed or from where the new mix would originate, is 15 miles from the project.

Approximate BTU requirements for each construction function involved, generally accepted as reasonably accurate, are as follows:

2,500	BTU to produce one gallon paving asphalt
5,000	BTU to haul one ton one mile
20,000	BTU to mix one ton of cold-mix (no recycling agent)
70,000	BTU to produce one ton aggregate
150,000	BTU per gallon of paving asphalt
250,000	BTU to dry and mix one ton of hot-mix aggregate (no asphalt)

The weight of the asphalt mix is assumed to be 140 lbs./cu. ft. and is the same for all procedures.

Tests on the aged pavement indicate that 1.6% recycling agent is required. The new aggregate hot-mix will require 6% paving asphalt. Based on this information, energy requirements of the five different procedures can be compared in BTU values. However, BTU requirements, difficult to visualize, can be easily comprehended when converted to the equivalent in energy content of gallons of paving asphalt. The energy requirements of the four different recycling procedures and new aggregate hot-mix in terms of gallons of paving asphalt, are as follows:

100% recycled aggregate mix cold on-site	70,000 gallons
100% recycled aggregate mix cold off-site	79,000 gallons
70% recycled aggregate, 30% new aggregate hot off-site	88,000 gallons
50% recycled aggregate, 50% new aggregate hot off-site	106,000 gallons
100% new aggregate hot-mix	155,000 gallons

These figures do not include the energy requirements for breaking up the old pavement, laydown and compaction since these values would be approximately the same whichever procedure is used. The above figures speak for themselves and should require no further comment except that recycling, especially the cold procedure, saves energy - a most important consideration not only at this point in time, but also in the foreseeable future. And, as mentioned previously, saving energy relates directly to savings in dollars.

RURAL COLD RECYCLING

Stewart R. Spelman, Region 15 Federal Highway Administration, U.S. Department of Transportation.

Cold recycling of deteriorated pavements in two National Parks is discussed. Information on the cost saving is presented. A tabulation of some cold recycle projects is presented. It is concluded that cold recycling is a viable economic rehabilitation process.

This paper covers rural recycling. Specifics on one recycling project in an eastern National Park are presented, a summary of a second Park project, and tabulation of other cold recycling projects are given.

The specific project discussed is one built in the Cape Cod National Seashore Park in Massachusetts. This project consisted of recycling an existing pavement in place. The roadway was closed to traffic during the construction except for emergency traffic. This project was successful and presented no problem.

The second Park project consisted of recycling an existing pavement after removal in Catoctin Mountain Park near Thurmont, Maryland. Part of this second project used an emulsion as a compaction aid. This project had a number of problems from which modifications for future projects of this type are under consideration.

Cape Cod National Seashore Park

This project consisted of reconstruction of 0.96 km (0.6 mi) of Moor's Road and 3.52 km (2.8 mi) of Province Lands Road in the Cape Cod National Seashore located near Provincetown, Massachusetts.

The existing pavement on 2.56 km (1.6 mi) of the Province Land Road consisted of 10 cm (4 in) of bituminous concrete (two, 5 cm (2 in) wearing courses of different ages); 10 cm (4 in) of sand-asphalt; and 15 cm (6 in) of a sand-clay mixture over a sand subgrade.

The remaining 0.8 km (0.5 mi) of Province Lands Road had a similar section. This portion of the road had been recently rebuilt and had only minor surface cracking so it was overlaid with 3.13 cm (1.25 in) of hot bituminous concrete.

The existing pavement on 0.96 km (0.6 mi) of Moor's Road was also recycled. The layers in this roadway were as follows: 7.5 cm (3 inch) of old bituminous concrete surface; 7.5 cm (3 inch) of sand asphalt; and 15 cm (6 inch) of sand-clay mixture. This section of the roadway had been recently rebuilt and had only minor surface cracking.

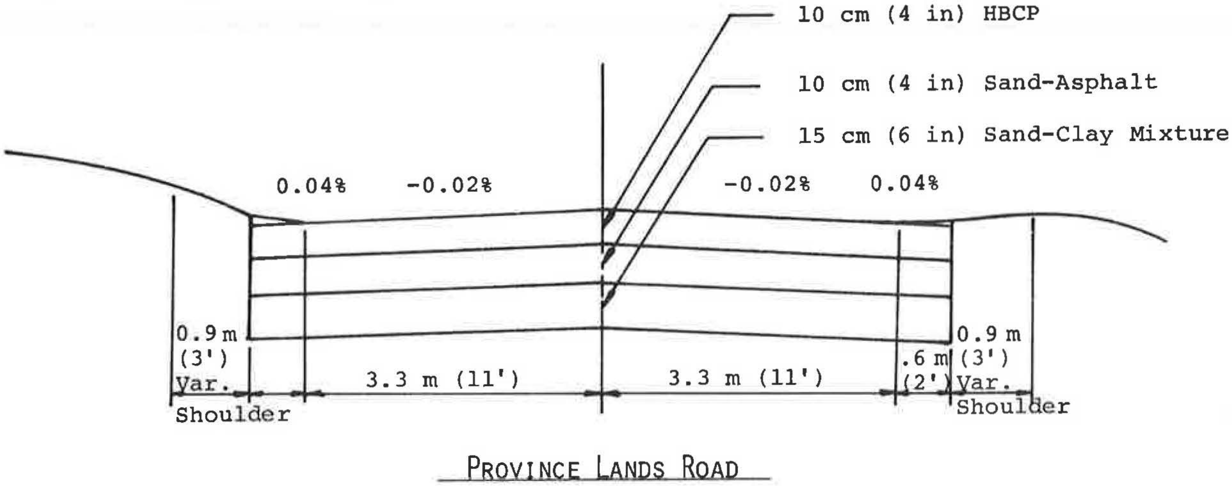
The typical sections for the two roads as they existed prior to construction appear in Figure 1. The existing pavement condition of these roadways is shown in Figures 2 and 3. Thermal cracks are evident in both roadways. The existing asphalt appeared to be oxidized and brittle and to have undergone considerable oxidation since placement.

The National Park Service recommended that reprocessing and relaying the existing roadway material prior to placing a new wearing course be considered during the design stage in lieu of adding a new leveling course and wearing course to the existing pavement.

Pavement Design

Based on the findings of the field investigation, on the flexible pavement design analysis (1, 2), and considering the National Park Service's request, the following pavement structures were recommended. See Figure 4.

Figure 1. Typical roadway sections before construction.



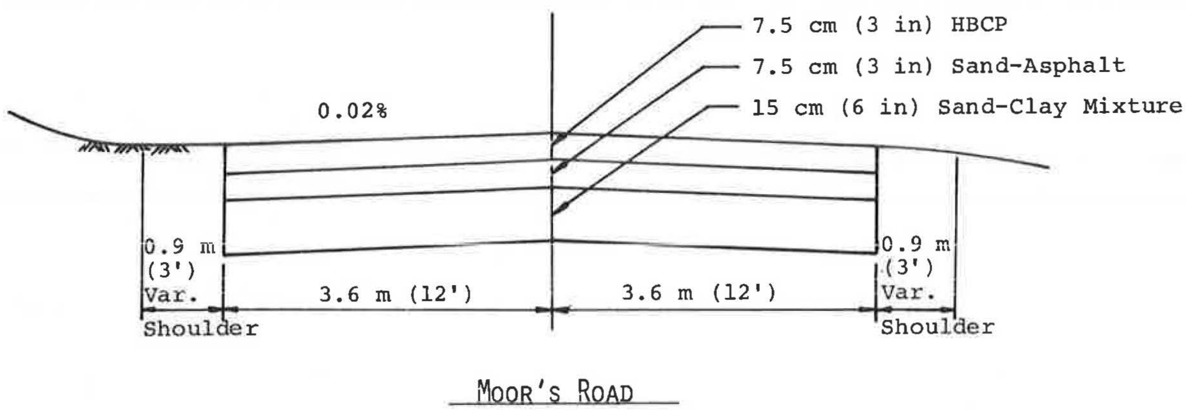
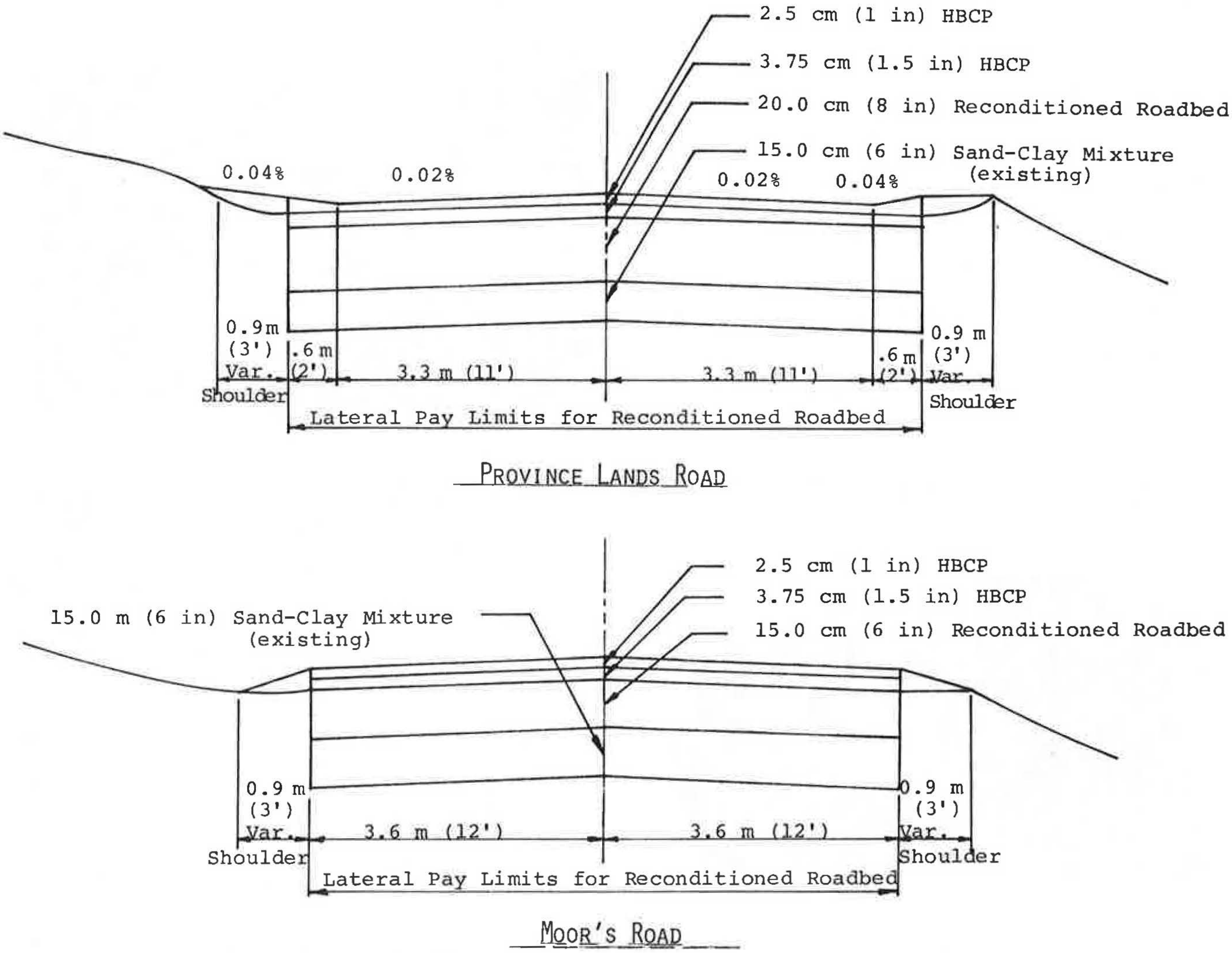


Figure 2. Transverse cracks in the existing pavement.

Figure 3. Localized deterioration in the existing pavement.

Figure 4. Typical sections for new roadways.



1. Province Lands Road. Section 1 (2.56 km (1.6 mi)).
   6.25 cm (2.5 in) hot bituminous concrete
   20.0 cm (8.0 in) cold recycled material
2. Province Lands Road. Section 2. (0.8 km (0.5 mi)).
   3.12 cm (1.25 in) hot bituminous concrete
3. Moor's Road (0.96 km (0.6 mi)).
   6.25 cm (2.5 in) hot bituminous concrete
   15.0 cm (6.0 in) cold recycled material

Pulverization and cold recycling of the existing bituminous surfacing material was recommended in lieu of overlaying to prevent reflective cracking and to provide a base of uniform strength and cross section. A layer coefficient of 0.25 was used for the recycled pavement in this analysis. This is equivalent to the value normally recommended by the AASHTO pavement design guide (2) for cold mix material.

Construction

Contractor. The prime contractor for this project was M. F. Roach of North Eastham, Massachusetts. He subcontracted the recycle work, called "reconditioning of roadbed" under this contract, to Bell and Flynn of Stratham, New Hampshire. They had done previous work of this type for the State of Maine, so were familiar with this type of operation.

Recycling. Reconditioning of the roadbed was accomplished by cold recycling the existing 20 cm (8 in) of bituminous pavement. A grader equipped with a ripping tooth scarified the existing pavement into relatively small pieces ie. 30 cm (24 in) by 90 cm (36 in) or less. The material was then bladed into a windrow. A BROS preparator, portable hammermill, was then towed by a front end loader over the windrow. After each pass of the hammermill the material was reformed into a windrow for additonal passes of the BROS preparator until the material was broken down to the desired size and uniformity. The specifications required 100 percent passing the 5 cm (2 in) sieve. There was no problem meeting this requirement with this material since it was primarily sand-asphalt concrete, which readily broke down under the action of the hammermill. Water was added during the processing with the hammermill to control dust, and keep the hammers cool by reducing friction. After the material was properly pulverized it was shaped by the grader and compacted. See Figures 5, 6, and 7.

Figure 5. Front end loader towing BROS preparator.

Figure 6. BROS preparator pulverizing windrowed material.

Figure 7. Partially compacted recycle material.

The project was designed for the finished grade of the recycled base material to match the original grade of the old roadways. Due to the recycling process and widening of the roadways this could not be accomplished and the finished grade of the base material was lowered approximately 3 cm (1.2 in). This did not affect the overall depth of the base material.

A prime coat was not used on the cold recycle material as the existing roadways had been constructed on a layer of clay or "hardening" used as the subbase to bridge the underlying sand. This added clay helped to make the resulting recycled base very tight and impervious to the penetration of the prime so it was eliminated.

Compaction. The compaction requirement for the recycled base material was 95 percent of AASHTO T-180 Method D (3). Since asphalt was present, a correction factor had to be determined for the nuclear density gauge being used to control compaction. This was done as recommended by the manufacturer of the gauge. A Troxler Model 3411 moisture-density gauge (4) was used.

Bituminous Concrete. A 3.75 cm (1.5 in) hot bituminous concrete binder course was placed over the recycle material and was followed by a 2.5 cm (1 in) wearing course. The gradations for the binder and wearing courses met the Massachusetts Specifications for Class I bituminous concrete pavement (5). These are nominal 1.9 cm (3/4 in) and 0.38 cm (3/8 in) dense graded mixes. These mixes were placed using a Blaw Knox track paver and compacted with two, 2-axle tandem steel rollers. See Figures 8 and 9.

Berms. Since the prevalent material on Cape Cod is sand and it is highly erodable along highways, surface drainage is controlled by the use of "Cape Cod" bituminous concrete berms and waterways. Figures 9, and 10 show the placement and end product of this operation.

Cost Comparison

Equivalent Hot Mix Cost. A cost comparison between the recycled pavement and an equivalent amount of new hot mix was made.

The structural coefficient for the recycled mix was assumed to be 0.25 as mentioned before. For the 20 cm (8 in) recycled pavement on the 2.56 km (1.6 mi) of Province Lands Road, 12.5 cm (5 in) of hot mix would be needed for an equivalent thickness using 0.40 for the hot mix coefficient. At a price of \$19.80/t (\$22/ton) this 12.5 cm (5 in) section of hot mix would cost \$139,000.

For the 15 cm (6 in) of recycled pavement on the 0.96 km (0.6 mi) of Moor's Road, 9.38 cm (3.75 in) of bituminous concrete would be needed or 1476t (1640 tons) of 720 cm (24 ft) wide pavement. At a price of \$19.80/t (\$22/ton) this 9.38 cm (3.75 in) would cost \$36,000. The total would be \$175,000.

Figure 8. Placement of wearing course over newly placed binder course.

Figure 9. Compacting the wearing course.

Figure 10. Placement of bituminous concrete berm.

Figure 11. Completed section of berm.

Recycle Cost. The recycle was paid for under three different pay items. One was by 30.3 m (100 foot - station) for Province Lands Road, one by square kilometers (sq yds) for Moor's Road, and one for the water in 760 ML (Mgal) for all recycle.

The contract and total costs for these items were as follows:

1. Recycle-Province Lands Road
   30.3 m x \$4108.75/m = \$124,495
   (116.18 Sta. x \$1072/Sta. = \$124,495)
2. Recycle-Moor's Road
   2,424 m^2 x \$4.313/m^2 = \$10,454
   (3,030 yd^2 x \$3.45/yd^2 = \$ 10,454)
3. Water
   760 ML x \$2.631/ML = \$2000
   (200 Mgal x \$10/Mgal = \$ 2,000)
   Total = \$136,949

Savings. Based on this data the savings would have been as follows:

Additional hot mix	\$175,000
Recycle mix	\$136,949
	\$ 38,051

This amounts to $38,051/3.52 km (2.2 mi) = $10,810/km ($10,378/0.6 mi). This does not include the added hauling cost to dispose of the old pavement.

Summary

This project proved very successful in that there were not any construction problems and the completed pavement looked excellent. See Figure 12. Also, the roadway has not shown any signs of problems in its one year life.

Figure 12. View of completed pavement.

Catoctin Mountain Park

Project Location

This project consisted of recycling an existing Pavement in Catoctin Mountain Park near Thurmont, Maryland. This location may be familiar to the reader because "Camp 3" or "Camp David," the President's retreat, is adjacent to the park grounds. In fact the construction work on this project had to be discontinued when the Egyptian - Israeli Summit Conferences were held there in 1979.

Construction

The project was four miles long and included reconstruction of the existing pavement with some widening and some new alinement. The roadway was essentially closed to traffic during construction. The existing roadway that was recycled consisted of a 5.4 m (18 ft) wide pavement of variable depth bituminous concrete of 7.5 cm (3 in) to 20 cm (8 in) thickness, the latter thickness being at the pavement edge. A CMI PR-750 Roto Mill was used to remove the old pavement - see Figure 13. The thicker pavement at the edges of the roadway that was not removed by rotomilling was crushed in place with a D-7 dozer and became part of the subgrade.

The material removed was stockpiled at two parking areas adjacent to the main roadway. A "Pelican" portable pugmill was used to mix the blend of 50 percent recycled material and 50 percent crushed stone with 4 percent emulsion (SS-1h). and 1 percent water - see Figure 14. The material was then placed on the prepared subgrade with a Barber Greene Paver and compacted with a 10-ton Hyster roller - see Figure 15. The final 5 cm (2 in) bituminous concrete overlay was placed after the recycled material had cured.

Figure 13. Roto-Mill removing old pavement.

Figure 14. Portable pugmill mixing emulsion with recycle-aggregate blend.

Problems

There were some problems encountered on this project as follows:

1. The stockpiled recycle material hardened in storage and had to be broken down with a bulldozer.

Figure 15. Placement of recycled material.

2. There were some oversize pieces in the stockpile because the Roto-Mill did not break up alligatored pieces of pavement during removal. These had to be scalped on the feed bin to the pugmill.

3. Crushed stone had to be blended with the recycle material to facilitate feeding the material through the cold feed hopper.

4. The maximum particle size requirement of 7.5 cm (3 in) for the recycled material prevented converting the lift thickness to two 5.0 cm (2 in) thick lifts to accelerate curing of the SS-1h emulsion.

5. The late fall season and forest location with considerable shade and high humidity caused delays in curing the emulsion type used here.

Specification changes

Based on this experience we are considering the following specification changes on future projects of this type.

1. Cement should be used with all slow set emulsions.

2. The use of mixing grade emulsions should be allowed as an alternate to the slow set type, particularly when the project may carry over into the late fall, the work is to be done in high humidity areas, and/or the use of pugmill mixing and machine placement is utilized.

3. Some laboratory and in place strength measure should be incorporated into the specifications for material containing an emulsion for a compaction aid.

Other Projects

There have been many reports (6,7,8) in the literature describing cold recycling projects on interstate highways, county and State roads, city streets, and park and Indian reservation roads. Various additives and/or stabilizing agents such as lime, liquid asphalts, emulsions, asphalt cements, and portland cement have been used. The end use of these cold recycled materials has normally been as a base material and usually protected by a bimuminous overlay or seal coat. Table 1 presents a summary of some of these projects.

Summary

Cold rural recycling is a viable construction procedure that utilizes existing materials in an economic manner and provides improved roadway structures.

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Table 1. Cold Recycling Projects (6,7,8).

State	Roadway	Recycled Material	Agent	End Use
California	S.R. 45	A.C. Pavement and base bituminous materials	Lime	Base 6.25 cm (2.5 in)
Indiana	C.R. 28/80	A.C. Pavement and gravel base	Chemical + Liquid A.C.	Base
Maine	I-95, S.R. 9, S.R. 17	A.C. Pavement	Cut back + emulsion	Base
Michigan	I-75	A.C. Pavement	Asphalt Cement	Base
North Dakota	US 281	A.C. Pavement	none	Shoulder
Kansas	S.R. 568	A.C. Pavement	Cutback	Pavement (+seal)
Texas	US 277	A.C. Pavement	Rejuvenation & emulsion	seal
FHWA (Reg. 15)	C.R. "M"	A.C. Pavement	Chemical & none & Emulsion	Base
FHWA (Reg. 15)	Cape Cod NSP	A.C. Pavement	None	Base
FHWA (Reg. 10)	BIA Reservation	Emulsion Base	Emulsion	Base
California	C.R. (Modoc)	A.C. Pavement + untreated base	Cement	Base
Illinois (Peoria)	City Streets	A.C. Pavement	Cement	Base
Utah	US 160	A.C. Pavement	Cement	Base
Nevada	US 40	A.C. Pavement + base	Cement	Base
Alabama (Montgomery)	City Streets	A.C. Pavement + base	Cement	Base
Virginia	City Streets	A.C. Pavement + base	Cement	Base

STATE-OF-THE-ART HOT RECYCLING

Richard W. Smith, National Asphalt Pavement Association

Hot recycling pertains to the recycling or reprocessing of reclaimed pavement materials into hot mix asphalt in a central plant. Although reclaimed uncoated, aggregate and Portland cement concrete materials can be reprocessed into hot-mix asphalt, hot recycling is usually meant to specifically include the reprocessing of reclaimed hot-mix asphalt or asphalt treated aggregate. Reclaimed uncoated aggregate materials are reprocessed in the conventional manner as new aggregates, whereas reclaimed asphalt coated aggregates are reprocessed using slightly modified techniques. Both reclaimed uncoated and coated aggregate materials may be reprocessed into hot-mix asphalt during the same operation. In either case, the use of some additional new aggregate may be required in the recycling process for the purpose of producing a hot-mix asphalt which meets the stated quality criteria for the mix and/or for the hot-mix plant operation, itself, which requires a certain quantity of uncoated aggregate to operate efficiently and within air quality standards. In all instances new asphalt cement and/or a suitable rejuvenating agent will also be added as part of the recycling process to restore the properties of the aged asphalt and to coat reclaimed or new aggregates that have been added. Hot recycling can be done in any type of hot-mix plant including the drum, batch, and continuous types. The hot-mix plant must be modified or retrofitted for recycling, if not originally equipped when new. In terms of overall plant replacement cost, the investment is relatively small. The actual hot recycling process is not complicated, and in fact not much different from the conventional process. The technology and equipment necessary to do recycling is developed and available. What makes hot recycling seem complicated sometimes is the seemingly infinite number of ways to go about it. In addition there are numerous factors unique to the highway industry and the asphalt industry in particular, that would make one recycling technique preferable in one area and not in another. These factors need to be addressed in order to meld hot recycling into the normal operating procedures of the asphalt paving industry. The concept of hot recycling has grown from one concerned with the utilization of pavement materials being disposed of in landfills to one also concerned with finding situations where pavement material removal for subsequent recycling provides an economic advantage over other pavement rehabilitation alternatives. It is the latter that is the most difficult to identify and to accomplish.

THE ROLE OF PAVEMENT MATERIAL REMOVAL AND RECYCLING IN PAVEMENT REHABILITATION

Obviously, if one is going to recycle, one must obtain pavement materials from some place. Since approximately 80 percent of all hot-mix asphalt produced is purchased by public agencies, only approximately 20 percent commercial and private, one could assume that potentially 80 percent of all recyclable materials will come from public owned pavements. Hence, the public agency is, or will be, the keystone in providing the bulk of materials for hot recycling and the manner in which they perceive and practice the concept of hot recycling is all important in determining the quantity of materials that will ultimately be made available for recycling. The estimated quantity of materials to be made available, as the hot-mix contractor interprets the agency attitude toward recycling, is all influential in motivating the necessary equipment purchases and modifications to do recycling. This in turn also has a rebound affect on the agency attitude. Hence negativism on one side will bring deeper negativism on the other side. Conversely, a positive attitude has a similar, but opposite effect.

Hot recycling has been considered by some to be a pavement rehabilitation alternative. In other words, the entire procedure of removing pavement materials and reprocessing them through the hot-mix plant to subsequent replacement in the pavement is compared against other alternatives, as for example, an asphalt overlay. Others consider that pavement material removal is the rehabilitation alternative and that hot recycling is a separate process. In other words, pavement material removal can be done independently of recycling and vice-versa, or both can be combined and planned together as above.

The National Asphalt Pavement Association and The Asphalt Institute have adopted the second point of view and have published the following definitions associated with hot recycling.

DEFINITIONS RELATED TO RECYCLING OF PAVEMENT MATERIALS

Pavement Material Removal - A pavement rehabilitation alternative.

Methods of Material Removal

(1) ripping and crushing
(2) cold milling
(3) hot milling
(4) heater planing

Reclaimed Asphalt Pavement (RAP) - Removed and/or processed pavement materials containing asphalt and aggregate.

Reclaimed Aggregate Material (RAM) - Removed and/or processed pavement materials containing no reusable binding agent.

Recycling - The reuse, usually after some processing, of a material that has already served its first-intended purpose.

Hot-Mix Recycling - A process in which reclaimed asphalt pavement materials, reclaimed aggregate materials, or both, are combined with new asphalt, and/or recycling agents, and/or new aggregate, as necessary, in a central plant to produce hot-mix paving mixtures. The finished product meets all standard material specifications and construction requirements for the type of mixture being produced.

It is important to recognize that the two operations, pavement material removal and recycling, are separable. There will be situations where it will be advantageous to combine them as a single rehabilitation plan and there will be situations where only pavement material removal is desired, and still other situations where no pavement material removal will be done, but recycling would be permitted if other material were available.

FACTORS INFLUENCING THE DECISION TO RECYCLE

There can be instances where if the two operations are not combined and other situations where if they are combined, then no recycling will be done because there are a number of associated factors which can make recycling seem to have the lesser economic advantage. Some of these are listed below:

A. Size of project (Recycling Ratio)
B. Availability of asphalt plants modified for recycling
C. Salvage value of removed pavement materials
D. Pavement material ownership policy
E. Reclaimed asphalt material content of resultant hot mix
F. Types of asphalt plants permitted/available
G. Location of project (rural or urban)

Almost all of the above factors are interactive with one another. For example, there are almost as many different situations that one has to contend with as there are possible combinations of the above factors. For this reason it is difficult to discuss each of these factors separately as the effect of each on whether recycling will be done can be different depending on the other factors. It is essential that the ultimate decision on whether recycling should be done, however, be based upon a life cycle cost analysis.

Initial cost is sometimes used as the basis with no consideration to the future costs of the various rehabilitation alternatives. Hence it is possible that recycling will be rejected as an alternative because initial costs might be higher, yet it could be the most economic choice based on annual cost over a specified service life. Part of the difficulty in life cycle analyses is the uncertainty of pavement service life of all types of pavements, in general, future repair needs, and availability of future funds for planned maintenance or rehabilitation programs. One cannot hope, however, to make a rational selection of any pavement rehabilitation alternative without some consideration to life cycle cost analysis of all possible alternatives.

A. Size of the Project

This factor needs to be considered in two parts; (1) tonnage of hot mix to be removed and, (2) tonnage of hot mix to be replaced. A secondary factor that is very influential is the recycling ratio, which is the ratio of the amount of material removed to the amount of material replaced.

If this ratio is greater than 0.7 (it is assumed here that a rehabilitation plan has been selected that is adequate structurally to handle the projected traffic over the desired service life at the desired pavement serviceability level), there will in all probability be excess reclaimed asphalt pavement materials left over after the project is completed. The economic value (salvage value) of this excess material is dependent on whether there is another place to use it within a reasonable haul distance. If there is no other place to utilize the economic value of the excess material, the agency should consider increasing the tonnage replaced to lower the ratio to at least 0.7 (increase pavement thickness above projected level of need, pave shoulders, etc.). This decision should be based on the economics of life cycle cost analysis as the two resultant pavements will have different service lives, different rehabilitation needs in the future, and different annual costs (or present worth). If there were another nearby location for use of this excess material, the economic value of the excess materials could be subtracted from the initial cost of this project or if the contractor purchased the excess material from the agency, the same effect is obtained. Then the recycling ratio would not have to be lowered.

In the above example, it was assumed that a drum mixer plant was to be used. If there are no drum mixer plants available, or if the agency does not want to exclude the use of batch plants, the recycling ratio should be lowered to at least 0.5. This limitation, as well as the preceding one, is mentioned because of plant type recycling limitations which will be discussed later. Depending on the number of drum mixer plants available, this latter course of action could improve the economics of recycling by stimulating competitive bidding. However, the economics may have been worsened because more hot-mix material is being replaced than originally determined to be necessary or wanted for the desired service life. A life cycle cost analysis would help determine whether or not this is the case.

A project designed with a recycling ratio of 0.7 in conjunction with a batch plant which has a maximum limitation on the reclaimed material content of the resultant mix of 0.5, means that excess material would be left over after project completion, whereas with a drum plant, it quite possibly would not. In instances where there is other possible use of the excess material (either on another public project or if the excess material becomes the property of the contractor it could be used on private or commercial work), it may be economically justified to still plan the project at a recycling ratio which exceeds the reclaimed material content capability of the batch plant (or even above that of the drum plant for that matter). The batch plant owner can only be competitive in this instance with the drum plant owner if he acquires ownership of the excess pavement materials rather than the agency retaining ownership, and if the former can find an economic use for the excess material on some other project either public, commercial, or private.

In instances where there is no other possible use of any excess removed materials either public, private, or commercial (no economic value) it is quite likely that the use of a drum plant will prevail and will provide the lowest cost to the agency, but this may not be guaranteed unless there are several drum plants available to provide the competitive bidding necessary for the lowest possible cost.

The industry has barely begun to gear-up for recycling. This is because recycling is not permitted on a routine basis. Of the 4,000 plus or minus batch plants and the 800 plus or minus drum plants in the United States, it is extremely doubtful if there are more than 100 plants that have been completely modified or have the recycling capability. Contractors are aware that recycling is a process that will gain momentum in the years ahead. Partial plant modifications are typically included when a new plant is purchased. The auxillary accessaries are not purchased but left until such time as a recycling opportunity becomes a reality. Therefore before a "recycling project" (remove material and reuse in same pavement) can be done, it is likely that the contractor on an average will have to expend approximately $50,000 to $75,000 to modify his plant. With no other definite prospects to recycle in the future, (no permissive statewide specification for routine reuse of removed materials) this equipment purchase will be figured into his bid. Thus, if the "recycling project" does not have sufficient tonnage to be replaced, this extra cost could negate the savings obtained from the value of the removed pavement materials. There is therefore a lessor chance, at the present, that pavement material removal and recycling on the small remotely located paving project can be economically feasible under these circumstances. In the future when more asphalt plants have been equipped for recycling, pavement material removal and recycling will be more feasible economically for the small remotely located project because the equipment modification will have been paid for or is being amortized.

We have been assuming here that the pavement materials, if removed, would have no other use but to recycle them back into the pavement structure from which they were removed and any excess material had no other use and a zero salvage value. For the small "recycling project" located within a reasonable haul distance to an asphalt plant, the same situation is evident except that the reclaimed pavement materials can be stockpiled by the contractor (thus their economic value is inventoried) for use at some later time when more modified plants become available. It is economically disadvantageous for the public agency to stockpile the excess material. The reasons for this are discussed later.

B. Availability of Asphalt Plants Modified for Recycling

As discussed previously, relatively few asphalt plants are equipped for recycling. Unless a potential "recycling project" is located near one of these, the "recycling project" will have to be sufficiently large to overcome the cost of the plant modification in order for recycling to be the most economic rehabilitation alternative and/or an immediate use seen for any excess removed pavement materials. Public agencies can stimulate the contractors to begin making the necessary modifications to do recycling by adopting a permissive specification which permits the contractor to use reclaimed pavement materials in the hot-mix asphalt he produces for them. If a contractor is permitted to do this on a routine basis and not just on a project basis the necessary capital equipment modification can be amortized over several years of work (tonnage) rather than on just one project. This approach accomplishes not only the same thing as a large single recycling project, but much more. Instead of only stimulating the modification of one plant, many contractors will be encouraged to make the modification. This would be especially true when they begin to obtain a number of projects where pavement materials are being removed as part of the pavement rehabilitation plan and they begin to develop stockpiles of these materials.

C. Salvage Value of Reclaimed Pavement Materials

The salvage value of reclaimed asphalt pavement materials is equal to the value of the asphalt and aggregates less the costs to remove and haul these materials and any costs necessary to prepare them for the recycling process. The value of reclaimed aggregate materials or concrete are less because no binding agent is present. In the case where cold milling was used to remove the materials, they may essentially be sized enough for recycling without any other processing except perhaps for scalping of a small percentage of oversized chunks.

In the event where pavement material removal was performed because there was no other alternative available, (the base had failed and additional overlays would have been fruitless), or where the savings derived from pavement material removal resulting from not having to reposition bridges, curbs, gutters, manholes, guard rails, overhead signs, raise shoulders, etc., exceeds the cost of pavement material removal, the salvage value of the removed materials is equal to the cost of replacement materials.

This latter situation illustrates where pavement materials can be removed assuming a zero salvage value. That is, they will be removed regardless if any recycling is intended to be done. Typically, this material has been disposed of in landfills, etc. Today there are a number of contractors who have substantial quantities of these reclaimed materials stockpiled at their plant sites that have been obtained in this manner, but with little opportunity to use them.

A public agency can obtain additional benefits from those stockpiled materials (even though the contractor now possesses them) by simply permitting the contractor to use those materials in the mixes he sells to them. Several state highway departments have taken this approach and permit the addition of reclaimed materials to base course mixes provided that conventional mix specifications are still met. The use of reclaimed materials in surface courses is still considered experimental. Although there will always be a need for the large "recycling project" where pavement removal and recycling will be tied together it is the small urban or city projects that will be done where pavement material removal and recycling are best performed as separate operations. It is the permissive specification approach which will provide the impetus for the asphalt industry to modify more plants for recycling. This in turn will eventually make possible the small rural "recycling project" which doesn't occur now because the equipment modification costs exceed material savings. Eventually, the permissive specification approach will provide competitive bidding for removed pavement materials (through lower bid prices for removal provided that the bid transfers ownership to them) among contractors until the salvage value ultimately equals the cost of new materials less removal and handling costs.

The public agencies need only consider the salvage value of removed materials that they will get in determining whether pavement material removal is to be part of the rehabilitation alternatives selected. If the material ownership is transferred to the contractor as part of the bid, then recycling need not be considered in the rehabilitation analysis. Full value for these materials will be obtained provided the project is situated in a location where any excess or surplus of removed materials could be used elsewhere. In these cases, the agency need not be concerned with the recycling ratio.

D. Pavement Material Ownership Policy

Most of the recycling done to date has been on the large "recycling project". Typically the recycling ratio on these projects have been from 0.5 to 0.7. In some instances recycling ratios have approached unity. Due to one reason or another the reclaimed material content of the resultant recycled mixture has also been made equal to the recycling ratio. The principal reason being that all pavement materials that were removed were consumed on that project so there were none left over. This can possibly be justified on the remotely located project where the economics of having left over material is not as satisfactory. However, for the project located near other potential places for reuse of any excess materials, the above practice is quite likely less cost effective.

In order to recycle at reclaimed material contents from 0.5 and greater, one must in all likelihood use a drum mixer plant. Not only has the batch plant been excluded from the bidding process in these circumstances, but even the drum plant has difficulty sometimes in recycling at these higher reclaimed contents. Depending on the nature of the materials being reprocessed, difficulty may be encountered in meeting air quality standards, particularly in regard to stack opacity. Techniques that have been used to combat this problem include lowering production rate and adding water to the reclaimed asphalt pavement materials on the cold feed belt as they are introduced into the plant. These procedures cost money to the contractor in increased hours of production and higher fuel consumption to remove the extra added water. These uncertain costs are more than likely figured in the bid price for the project.

In most recycling projects to date, the public agency has retained the ownership of removed asphalt pavement materials and has designed these projects so that the reclaimed material content was equal to the recycling ratio to eliminate excess material after the project conclusion. This is not considered good practice from an economic viewpoint and not condusive to producing quality hot-mix asphalt. For remotely located projects this plan of action may seem to be economically justified. However, the extra costs of production at high reclaimed contents may be greater than the value of some excess material after the project's completion. Where there may be other uses for the excess material on other projects in the vicinity, high reclaimed material contents are unjustified economically.

The National Asphalt Pavement Association recommends that the ownership of removed asphalt pavement materials be transferred to the contractor through the bid document and that bid items be included for the removal operation and for the salvage value of the materials. In some cases, public agencies have retained ownership of the reclaimed materials (or the excess) and have stockpiled them with the intent of using those materials in future paving contracts. Besides the expense in storing the materials (cost of land, prevention of theft, tarps to cover the materials), the agency also then assumes the responsibility (an implied warranty) that the materials in that stockpile conform to specifications when they direct a contractor to use it in his hot-mix asphalt.

NAPA's recommended bidding procedures are as follows:

1. The bid procedure should permit the contractor to add any percentage of reclaimed asphalt pavement to the mix he selects as long as the stated test properties of the mix are met. Specific percentages should not be a requirement of the bid. A new job mix formula should be required each time the percentage is changed.
2. If removal of asphalt pavement or other layers from the road is required, a bid item for removal should be included.
3. Where removal is required, (2 above) the contract should state that the removed material belongs to the contractor and bid items included for the salvage value of the material. The salvage value bid by the contractor will be subtracted from the total bid price if the bid price is positive, or added if the bid price is negative.
4. The bid proposal should not require reclaimed pavement that is added to the mix come from the specific job described in the bid proposal. Other reclaimed asphalt pavement should be permitted as long as the stated properties of the aggregate and the mix are met.
5. Since unnecessary crushing of reclaimed asphalt pavement produces undesirable quantities of fines, the degree of crushing should not be specified, but should be left to the contractor.

These procedures are designed to give the contractor more flexibility in recycling. Uncertainties of recycling at high reclaimed material contents are eliminated. With a permissive or alternate specification for mixes containing removed materials, in effect, excess materials from one project can be used in other agency work as well as in the private and commercial markets.

The agency must consider the recycling ratio in designing the remotely located project, but need not be concerned on any project where other uses for removed materials are close by. The contractor will establish the reclaimed material content after the bid has been awarded in conjunction with his own capabilities and plans for excess material utilization.

E. Reclaimed Asphalt Material Content of Resultant Hot Mix

As mentioned above, if pavement material ownership is transferred to the contractor through the bid document, the reclaimed material content becomes his choice much as any other materials he chooses to utilize in the hot-mix asphalt he proposes to produce, while the recycling ratio is determined before the bid by the public agency and should logically be as compatible with the capabilities of the asphalt industry as possible.

The reclaimed material content is determined after the bid and logically so. One might ask the question, how can a proper hot mix be designed to meet quality criteria before a bid when the characteristics of the not yet removed materials are all influential in determining how much can be used?

Agency ownership of removed asphalt pavement materials has contributed to the use of high reclaimed (0.7 to 1.0) asphalt material contents. These high reclaimed material contents are counter-productive to high plant productivity and fuel conservation efforts if water is added to the process to meet air quality standards.

Contractor ownership of removed asphalt pavement materials will result in his using the reclaimed material content most profitable to him and, with adequate competiveness within the industry, will yield the greatest economic benefit to the public agencies. This does not necessarily mean that extremely low reclaimed material contents will be used, but rather a content as high as practical and profitable will be used which in all probability will be somewhat lower than used in the past. The principal factors include less wear and tear on plant equipment, greater probability of meeting air quality standards and job mix requirements, higher plant production rates, and lowered energy consumption.

The use of reclaimed asphalt material contents in excess of 0.7 (70/30) generally means that a recycling agent (or rejuvenating agent) in addition to a softer grade of asphalt cement may be required in the recycling process to reestablish asphalt cement qualities to that more compatible with conventional mixtures. At these higher reclaimed contents, the soft asphalt cement added may be insufficient in quantity to compensate for the amount of hardened asphalt in the reclaimed material. The use of recycling agents may affect the economics of high reclaimed content mixes as they are more expensive than asphalt cements. At lower reclaimed asphalt material contents, recycling agents are not generally required.

F. Types of Asphalt Plants Permitted/Available

As mentioned previously, the batch plant outnumbers the drum plant in the United States by a ratio of approximately 5 to 1. The sales of new asphalt plants finds that the ratio is almost reversed, namely five drum plants are sold for every batch plant. The principal reason for this is the lower cost associated with the operation of a drum plant. New plants are purchased when an old one wears out or when a contractor wants to increase his potential production capacity. Equipment renewal is an ongoing process for a healthy industry. The asphalt industry, in general, has been making a gradual transition from the batch to the drum type of plant. The facts above have a very profound affect on the acceptance of recycling by the asphalt contractors as has been practiced by the public agencies.

It is generally accepted that recycling in batch plants limits one to reclaimed asphalt material contents of 0.5 (50%) maximum and on a more practical basis, 0.3 and that recycling in drum plants may be as high as 0.7 (70%) maximum and on a more practical basis, 0.5. In past recycling projects, when public agencies have specified reclaimed asphalt material contents exceeding 0.5 (on projects with recycling ratios of 0.5 or greater, with agency retaining ownership of removed materials), they have essentially specified the use of a drum mixer plant. In areas of the country such as the western part of the U.S., where drum mixer plants are more prevalent, this has not created too much of a problem. However, in the more urban eastern U.S. where batch plants are more prevalent, this creates a problem if the public agency in the East tries to reapply techniques used in the West. In some eastern states where few, if any, drum plants have been accepted by the agencies, specifying recycling at reclaimed contents greater than 0.5 means that recycling cannot be done unless a drum plant is purchased. Either the agency does not want to permit drum plants or the contractors do not want to buy a new plant they don't immediately need and so recycling is not done on a mutual basis. Recycling in the eastern states is practically non-existent because of this. This of course can be easily changed.

Recycling can be done successfully in batch plants as well as drum plants. The key to accomplishing this is by, (1) transferring pavement material ownership through the bid document to the contractor, (2) permitting recycling to be done on a routine basis provided all mix quality standards are met, and (3) permitting the contractor to select the reclaimed asphalt material content he wishes and which is ultimately verified by a mix design analysis.

The idea that one needs a drum plant to recycle is erroneous and may in fact, have been inadvertently promulgated by asphalt plant sales literature that stresses the higher asphalt reclaimed material content potential of drum plants. The economics of recycling are separate and completely distinct from the economics of drum mixer versus batch plant operation. This fact has been clouded by unnecessary attempts to maximize the reclaimed asphalt material content in recycled mixes.

G. Location of Project (rural or urban)

Several aspects of this factor have already been discussed. The distinction between rural and urban for the purposes of this paper is more related to the salvage value of excess removed pavement materials. If one is not able to recycle them on a particular project from which they are removed or if there is no other possible use of the materials within a reasonable haul distance then the salvage value is essentially zero or possibly less. If the above is the case, one is essentially "rural," whereas if there is a positive salvage value, then one is "urban."

On "rural" projects, the agencies have in the past typically retained the ownership of removed pavement materials and have designed the rehabilitation project at very high recycling ratios, and subsequently, very high reclaimed asphalt material contents in the resultant mix (the same in most cases) to minimize the purchase of new materials and to eliminate excess reclaimed materials at the project's conclusion.

In most recycling projects, the above is actually "false economy." While agencies may have claimed savings on these projects in the past, it has only been because of a permissive attitude by the environmental control agencies who had typically given variances for many of these projects which were also designated experimental. In a number of cases air quality standards were not met during any part of the recycling operation. Variances will not be given in the future, and consequently the uncertainty of the plant operations being shut down and resultant fines (penalties) due to uncontrollable emissions at high reclaimed contents will certainly be figured in future bid costs.

In "urban" areas the forced use of high reclaimed asphalt material contents as a result of projects designed at high recycling ratios by agencies that retain pavement material ownership in particular, is even more uneconomical because these areas will also be the more populated, industrialized sections of the country. In "rural" areas there may be more time to bring the recycling process under control through plant and mix adjustments to meet emission standards; however, in "urban" areas, this practice will not generally be permitted or possible. These unknowns result in higher bid prices which can negate the "savings" an agency thought it could get by requiring high reclaimed asphalt material contents in the resultant mix.

RECYCLING TECHNOLOGY

The technology associated with pavement material removal is described as follows:

A. Pavement Material Removal & Processing

Some reclaimed asphalt pavement (RAP) will come from removal of the full thickness of asphalt on roads or streets being rehabilitated. The pavement can be broken up with ripper teeth on a dozer enough that it can be loaded into trucks with front-end loaders. In some cases it is necessary to further break the pavement into smaller size by grid rollers or equipment tracks before it is transported to the crusher site.

Contamination of the RAP with underlying base course causes no problem, but if the underlying untreated base course and subbase are to be reclaimed and used as the aggregate in the resultant mix, it is imperative that the underlying base not be contaminated with RAP or unacceptable smoke will be emitted from the dryer.

Crushing existing asphalt pavements has not created problems if the pavement pieces are first broken to a size which can be accepted by the various crushing components. Crushing in hot weather has not created any special problems to date. Experience has shown that crushing RAP does not require a heavy duty unit. Most crushing to date has been done by jaw and roll crushers; however, manufacturers are now working on units designed especially for this purpose. The size to which reclaimed asphalt pavement chunks should be crushed is determined primarily by the plant recycling process. It is important that the chunks are remelted and mixed thoroughly with the added new materials. However, if the maximum size of the aggregate particles in the reclaimed asphalt pavement chunks exceeds the maximum size permitted by the mix specifications, crushing must be done to reduce the maximum particle size to the specification limits. Unnecessary crushing of reclaimed asphalt pavement chunks only increases the amount of dust-sized particles and will have an uneconomic effect on how much reclaimed material can be used in the resultant mixture.

A substantial amount of RAP is expected from milling operations, either hot or cold, made to restore a given pavement to grade or to a lower grade. In this process a rotating drum equipped with special teeth cuts the pavement to a predetermined depth and reduces it in size in the process. Milling (cold planing) is primarily done to correct a pavement surface distress or to remove overlays. The material by-product resulting from milling is already reduced in size, and suitable for use in hot recycling without further reduction, except possible scalping off of oversized chunks.

Two features govern the storing of RAP. One is that RAP tends to stick together if stockpiles are high. The lowest stockpile height that space will permit should be used. The other is that the uncrushed RAP will absorb moisture in the stockpile. In the road, the pavement will have less than about one percent moisture, but the moisture can increase a percent or so in storage. If the pavement is crushed before stockpiling it will absorb a much higher percentage of moisture. More energy is needed to evaporate this moisture. The energy must come from the heated uncoated aggregate and since there is a limit on how hot the aggregate can be heated, particularly in batch plants, higher moisture contents means that less RAP can be added to the mix. Methods of minimizing moisture buildup should be considered. If scheduling permits, storing small quantities of crushed RAP would minimize moisture buildup. Protected stockpiles may be cost effective.

Crushed or milled RAP can pick up considerably more water than uncrushed RAP if exposed to rain. Moisture contents in excess of five percent have been measured in stored crushed RAP. Ingenuity is needed to prevent moisture buildup to conserve energy and permit using as much RAP as desired. If the crushing plant has the capacity, the stockpile of crushed RAP should be kept to the minimum needed to provide surge capacity.

Both rubber-tired and crawler-type loaders have been used with success in rehandling RAP. At times some reconsolidation may occur in which case the use of loader buckets with teeth is recommended. Driving on the stockpile should be avoided.

B. Plant Recycling Processes

Recycling can be done in either a batch type, drum mixer type, or continuous mixer type asphalt plant.

Batch Plant.

Hot recycling can be done in a batch-type asphalt plant by what can best be described as the "mixer heat transfer method." This method was first developed in Maplewood, Minnesota, and is also known as the "Minnesota Method."

In this method the reclaimed asphalt pavement (RAP) is fed to the plant weigh box at stockpile-ambient temperature by a handling system consisting of stockpiles, feeding bin, feeder and conveying mechanism while the required uncoated aggregate is processed through the regular plant feeding system, dryer, elevator and tower. This uncoated aggregate is superheated in the dryer and transfers its heat to the cold RAP in the plant mixer. Additional asphalt and/or softening agent is added there.

This process avoids both smoke pollution and material buildup problems by not passing the RAP through the plant dryer, elevator and screen.

The amount of RAP which can be used is determined (in order of importance):

1. The moisture content of the RAP.
2. The required temperature of the resultant mix.
3. The temperature to which the aggregate is heated.
4. The stockpile temperature of the RAP.

Present experience and calculations indicate that the amount of RAP which can be used in this method may be as high as 50 % of the total mix if the moisture content of the RAP is minimal and is fed to the plant at normal stockpile temperatures. A more practical amount is 30 to 40 percent.

Hot recycling of RAP by the mixer heat transfer method is being done satisfactorily in many sections of the country and modifications to permit recycling can now be installed on any conventional batch-type plant. There are, however, many points in the process which must be understood to assure good operation. These points will be emphasized in the following detailed description of the various parts of the process.

For a batch plant, the crushed RAP is fed to the plant with a conventional cold feeder except the bin should have a relatively small capacity with steep sides and a wide and long bottom opening to allow for easy discharge and minimal sticking problems. When RAP is fed into the feeder bin, it should be dribbled in as much as possible. It should not be fed to the bin as a unit drop since this causes compaction of the RAP with resultant bridging, sticking and discharge problems. Vibrators should not be used on this bin since they would only encourage compaction of the RAP. Both belt and slat type feeders have been successfully used. They should be fairly wide and should have sufficient horsepower to be used in a startstop operation as necessary. Vibrating type feeders are not recommended as they could also encourage the tendency of the RAP to consolidate and stick.

Basically two methods are used to transport the crushed RAP to the weigh hopper. One method uses a belt or other type conveyor to move the crushed RAP from the feeder bin directly into the weigh hopper. The conveyor width and speed should be such that the desired amount of RAP per batch can be discharged into the weigh box in sequence with the superheated aggregates from the plant hot bins without delaying the cycle. In other words, the RAP and the aggregates must be placed in the weigh hopper within the 40 to 60 seconds it takes the previous batch to be mixed, otherwise the cycle will be delayed.

The conveyor will be starting and stopping as directed by the plant weighing controls. The conveyor will require a backstop or anti-rollback device if it is fed by a feed bin unit equipped with feeder. The backstop may not be necessary if the feeding bin discharges directly onto the conveyor belt as the friction of the RAP on the belt would keep it from moving backward. A special-duty type motor might be necessary because of the start-stop operation. In lieu of this, a hydraulic or clutch-type mechanical drive might be used to permit continuous running of the conveyor power unit. The conveying device to the tower must be operated by the asphalt plant weighing control system as an additional material. The conveying device should be interlocked with the feed bin feeder so that both stop simultaneously.

The other method uses a special bin adjacent to the weigh box. The crushed RAP is fed into this bin by a belt conveyor or in limited space installations by a vertical or inclined elevator. If the bin does not discharge directly into the weigh box, a high-speed conveyor is necessary. The bin should have steep side slopes to avoid binding of the RAP.

The RAP should enter the weigh box as close to its center as possible to prevent material buildup on the weigh box sides. The RAP material <u>should not</u> be first in the weighing sequence for the same reason.

The area surrounding an asphalt plant weigh box and mixer is covered by a metal enclosure to prevent dust from escaping to the atmosphere. Pipes from the plant fugitive air system connect to the enclosure to aid in dust suppression. The amount of air that these pipes withdraw from the enclosure is sufficient for regular plant operations. It is also normally sufficient for the recycling process when RAP with low moisture content is fed to the weigh box.

When RAP with high moisture content is used, the heat transfer process in the plant mixer liberates large amounts of water vapor and the amount of vapor generated may be in excess of the exhausting ability of the fugitive air system.

To minimize dust entrainment in the escaping water vapor, the dry mix time should be minimized, and the asphalt discharge should commence immediately after the weigh hopper gates are opened. Water vapor and particulate emissions can be minimized by keeping the moisture contents of the reclaimed material as low as possible and/or reducing the proportion of RAP in the hot-asphalt mixture. If the volume of water vapor cannot be kept within the capacity of the fugitive air system, then the capacity of the system must be increased.

Hot mix containing reclaimed materials and made by the mixer heat transfer method can use up to 50% maximum of RAP. The remaining material will be new or reclaimed aggregates. These aggregates are processed through the conventional parts of the asphalt plant starting in the cold feed system. This system operates normally and no alterations are required. When the aggregate is processed through the dryer, it must be heated enough to provide the heat needed to bring the RAP up to the desired temperature during the heat-transfer process in the plant mixer. Aggregates have been heated to 500° F. (260° C) in recycling to date without serious problems, but even this may be too high for safe operation of a baghouse. If aggregate temperatures much higher than 500° F. (260° C) are used, caution is necessary in operating and cooling down the dryer.

These high temperatures require reasonable attention to the condition and arrangements of dryer flights to prevent excessive temperature of the dryer gases which exit into the dryer air system. It is particularly important that an adequate veil of aggregate be maintained. In recycling to date, excessive dryer gas temperature in the air system has not been common and can be prevented. The higher dried material temperature may result in a somewhat shorter than normal life for the discharge end flights of the dryer and also for the burner system refractories. This increased maintenance, however, should not be excessive.

At the end of each production cycle, the dryer drum should be allowed to run empty for a reasonable cooling period after production shutdown. This cooling period will protect against possible warping of the dryer shell and its internal parts. Because of the superheating of the aggregate in the dryer, the dryer exhaust gas temperatures may be higher than normal. Extreme exhaust gas temperatures can be prevented by proper arrangement and maintenance of the dryer flights. For plants with wet wash air pollution systems, the high exhaust gas temperatures present no particular problems.

For asphalt batch plants equipped with a baghouse, extremely high exhaust temperatures could damage the bags. Most baghouses use Nomex bags. If the gases entering the baghouse are continuously above 400°F. (204°C), the bag life will be shortened. At exhaust gas temperatures over 450°F. (232° C), the deterioration of the bag material would be greatly accelerated. Steps should be taken to keep the temperature of the exhaust gas entering the baghouse below 400°F. (204°C).

Upon discharge from the dryer, the superheated aggregate is carried up to the top of the batch plant tower by the hot elevator system. The only problems noted to date have been produced by excessive elongation of the elevator chains during operation and subsequent shrinkage on cooling. The elongation creates slack which may exceed the capacity of the take-up device. If the elevator has no take-up device and the shaft is moved to accomodate the elongation, the shaft must be moved back during cool-down or the shrinkage of the chain may break the shaft.

The superheated aggregate passes from the hot elevator over the batch plant screens. No problems should be encountered during the screening operation unless the screen bearings are located inside the dust housing. If so, excessive temperature buildup could occur in these bearings. Lubricants designed for higher than normal temperatures should then be used.

To prevent excessive temperature drop of the superheated aggregate consideration should be given, depending on the size of the bins and the material storage time, to insulating the outside of the hot bins.

No changes are needed to the asphalt cement delivery system unless a softening or reclaiming agent is to be added. The point of discharge of the softening agent, either into the asphalt weigh bucket or directly into the pugmill, depends on the requirements for each individual agent.

Drum Mixer Plant.

In this method reclaimed asphalt pavement is processed directly through the drum mixer together with uncoated aggregate. Additional new asphalt cement and/or softening agent is added in the drum mixer, and the discharged product is a recycled hot mix. The main problems in this type of recycling originally were smoke emissions from the asphalt cement portion of the reclaimed asphalt pavement (residual asphalt), and a material buildup inside the drum.

During the past years drum mixers have been modified so that the smoke emission problems have been virtually eliminated. This has been done by continuing to feed uncoated aggregate into the burner end of the drum mixer while the reclaimed asphalt pavement is now fed into the process at a point either partway down the drum or from the discharge end. This late introduction of reclaimed asphalt pavement is done by several different proprietary methods.

This type of operation uses uncoated aggregate to absorb the more intense heat of the burner flame, so that the reclaimed asphalt pavement receives heat from lower gas temperatures, and from the heat content of the uncoated aggregate. This results in no smoke emissions or very minimal emissions.

This process seems to require approximately a minimum thirty percent of uncoated aggregate to effectively cool the burner flame, resulting in the maximum use of approximately seventy percent of reclaimed asphalt pavement if the moisture content of the RAP is minimal and is fed to the plant at normal stockpile temperatures. The reason that the drum mixer can produce mixes using a slightly higher reclaimed asphalt material content, if desired, is because the mixture (after all ingredients have been combined) is subjected to additional heating during mixing from the exiting dryer gases.

Another method feeds both uncoated aggregate and salvaged asphalt pavement together into the feed end of the drum after first adding water to the dryer feed to moisten and help agglomerate the small residual asphalt particles in the reclaimed pavement. Atmospheric air intake which is increased, together with a special combustion tube-internal cone assembly, is then used to lower the temperature of the burner gases and prevent the burner flame from touching the cascading combined feed in the dryer. Reclaimed asphalt material contents higher than seventy percent are possible with this method when air standards can be met, but at a significant loss of plant productivity, mix discharge temperature, and increased fuel consumption per ton processed to evaporate the added moisture. These are the economic trade offs to utilizing all RAP when any excess would have no economic salvage value.

Material buildup has occurred in some drum mixers processing high reclaimed asphalt pavement contents. The buildup is a combination of some of the residual asphalt and minus 200 mesh portion of the material being processed. It can also be caused by the asphalt cement content in the original pavement, by sealing agents and/or special additives which were used to treat the pavement during its lifetime. It may also be caused by softening agents added in the drum mixer.

Continuous Mixer Plant.

The continuous mixer has not been utilized to any great extent for recycling primarily because there are so few of this type. Some recycling has been done, however, both in the United States and Canada with the continuous plant. The process would be quite analogous to the Maplewood concept for batch type plants and would have generally the same maximum limitations on reclaimed material content. An additional feeder is needed to input RAP into the foot of the hot elevator feeding the continuous pugmill. Reclaimed aggregate would be processed through the dryer in conventional fashion.

C. Spreading and Compaction

Conventional pavers and rollers have been used and no special equipment has been required to date in either spreading or compacting mixes containing reclaimed pavement materials. Work done shows laying temperatures ranging from 225° to 300°F.

D. Mix Design and Quality Control

Mix designs are developed using regular mix design test procedures and the results have been satisfactory in most instances. It is quite apparent that a very important part of recycling will be a thorough laboratory design and control of the recycled mix with particular emphasis on the aggregate gradation and asphalt characteristics of the reclaimed asphalt pavement. Quality control during recycling is equally important as in conventional hot-mix processing.

The goal of recycling is to produce a final product meeting the specified quality mix requirements of conventional mixes in all respects. In order to achieve the desired mix design, it is necessary to understand the material quality aspects of reclaimed pavement.

As an asphalt pavement ages in service, some changes which may have taken place during aging needs to be corrected. These changes can be summarized as follows:

1. Mineral aggregates: Degradation of aggregate particles sometimes occurs through wear and time resulting in changes in gradation from the original mix. The process of reclaiming, whether crushing or cold milling, can create further and more substantial degradation. If the reclaimed asphalt pavement contains an excess of fine material, additional coarser sized aggregate, which in turn may require more asphalt cement, will have to be added. The surplus of fines could be a combined result of those in the original mix, plus those caused by the size reduction of the pavement in the crushing or milling process.

2. Asphalt cement: By processes of oxidation, volatilization, aggregate absorption, and other chemical changes, the asphalt cement hardens and loses ductility. This hardening renders the pavement more susceptible to cracking and raveling as it ages. The aging is most severe at the surface due to environmental exposure and less severe within the pavement.

An analysis of the gradation in the reclaimed material can permit the contractor to add new aggregates of the required gradation to meet the final gradations specified in the mix design. Analysis of the properties of the reclaimed asphalt cement can permit the decision as to the amounts and specifications of new asphalt required to meet the properties specified in the designed final mix.

The reclaimed material content must be determined by mix design procedures with plant recycling limitations and the project recycling ratio in mind. In the past, reclaimed asphalt material content of the resultant mix was set equal to the recycling ratio (which was often maximized and above plant recycling limitations) with lesser regard for mix quality standards.

If mixes containing reclaimed materials are designed to meet the same criteria as conventional mixes, the structural design coefficients of recycled mixes should be the same as given to conventional mixes. If recycled mixes are to be designed on the basis of project recycling ratio requirements without consideration to established mix design procedures and mix design criteria, then the durability and structural relationship between recycled mixes and conventional mixes is a debatable one. RAP materials with more variable gradations and asphalt contents are best used at lower reclaimed asphalt material contents rather than loosening up specifications or quality design criteria. This enables the use of standard structural design coefficients for mixes containing recycled materials.

E. The Economics of Pavement Material Removal and Recycling

The economics of pavement material removal are dependent on the following:

1. The salvage value of the reclaimed pavement materials which is equal to the cost of an equal quantity of new aggregates and asphalt cement less the cost of pavement material removal, hauling, and processing.

2. The life cycle cost of the various pavement rehabilitation alternatives available as a result of pavement material removal. The recycling ratio is considered in these analyses.

3. The savings realized from not having to reposition manholes, guardrails, overhead signs, bridges, curbs, gutters, raising shoulders, etc.

The salvage value is further affected by (a) the nature of the reclaimed materials (gradation variability, type of aggregate, hardness of asphalt, etc.), (b) whether there is a market for use of the reclaimed material either on the particular project from which they are removed or on other projects (if there is a market, the recycling ratio is unimportant; if there is no market, the recycling ratio is a significant factor), (c) whether there is a permissive recycling specification in force, (d) the availability of asphalt plants equipped for recycling which is affected by many factors discussed earlier, and (e) the reclaimed material ownership policy in effect which determines whether the agency or the contractor sets the reclaimed asphalt material content in the resultant mixes, the level of which affects recycling economics.

The economics of recycling are dependent on the following:

1. The reclaimed asphalt material content of the resultant mix as it affects plant production rate, emissions control measures (such as adding water to cold feed), and the need for specialized rejuvenating agents.

2. The moisture content of the reclaimed pavement materials as it affects fuel consumption in the drying of aggregates and plant production rate.

3. The relatively small cost of plant modifications when computed on a tonnage basis.

The future for recycling is dependent on developing the economics of recycling above. It is estimated that in 1980, perhaps as much as 10 million tons of hot-mix asphalt contained some amount of reclaimed pavement matrials. The amount of reclaimed materials may have been as much as 4 million tons. As more persons understand and utilize the techniques of pavement material removal and recycling, the tonnages will undoubtedly get larger.

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EQUIPMENT FOR HOT RECYCLING

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Equipment for hot recycling can be divided into three categories -- 1) removal and sizing; 2) reprocessing; 3) laydown and compaction. Some pavements can be easily ripped full-depth and the reclaimed asphaltic material reduced to an appropriate size through a standard crushing operation. Cold milling machines can often be used to remove and size an asphalt pavement in a single operation. The reclaimed material can then be reprocessed along with additional new materials through a modified batch or dryer-drum plant to produce hot paving mixtures. Although many plant modifications have been tried, only a few are currently being used. These modifications allow plants to reprocess reclaimed asphaltic materials, producing a quality product at relatively high production rates within acceptable emission levels. Hot paving mixtures containing various percentages of reclaimed asphaltic material can be successfully used in a wide variety of applications and can be placed with standard laydown and compaction equipment.

Equipment for hot recycling can be divided into three categories -- 1) removal and sizing; 2) reprocessing; 3) laydown and compaction.

Removal and Sizing

Rip and Crush

Reclaimed asphaltic material is usually obtained from the mainline and/or shoulders of an existing roadway. The asphalt pavement may be removed full-depth by front-end loaders, bulldozers, or motorgraders (possibly equipped with special ripper attachments). This type of removal technique is primarily used when an existing pavement exhibits distress which can only be corrected by complete reconstruction. It may also be appropriate in cases where an existing base (or lower layer) must be replaced or reworked, where an existing roadway or detour is to be abandoned, where an existing roadway is to be realigned, or possibly where an asphalt overlay is to be stripped from an existing portland cement concrete pavement. Although it can be done one lane at a time, it is very difficult to maintain anything but low traffic volumes through a reconstruction project using this type of removal technique.

After ripping, the chunks of reclaimed asphalt are usually loaded into trucks and hauled to a central location. This material can be stockpiled for future use or it can be immediately crushed and recycled. Usually a standard crushing operation (jaw for primary and roll for secondary) is used to size the reclaimed asphaltic material prior to recycling. No attempt is made to rigidly control the overall gradation of the material; only to reduce all the chunks to an appropriate maximum size and to avoid creating excessive fines. No major equipment problems have occurred at the crusher on past projects; even on projects where the crushing was done in very hot weather.

Cold Milling

Cold milling machines may be used to remove and size an asphalt pavement in a single operation. Several equipment manufacturers (CMI, Barber-Greene, Barco, Galion, Gomaco, G.J. Payne, etc.) currently produce equipment of this type in various sizes and with varying capabilities. This type of equipment is primarily used on projects which require only partial depth removal of an existing pavement.

Figure 1. Cold milling machine.

Cold milling machines use a rotating drum with special teeth to cut a pavement to a predetermined depth and size the reclaimed asphaltic material. Single-pass cutting widths of up to 12 feet and depths of 4+ inches have been attained. The size of the milled product will vary depending on several factors -- number, type, arrangement, and condition of the cutting teeth; forward speed of the machine; depth of cut; and properties of the reclaimed material. The milled material will usually be suitable for hot recycling without further size reduction, although there may be a small percentage of oversize that will need to be screened or scalped off. There will usually be a slight increase in the aggregate fines as a result of milling. This increase has not been critical on past projects; in most cases, it has been easily offset by the additional virgin aggregate required for the hot recycling plant operation. Cold milling machines can leave an acceptable temporary riding surface, and traffic (even higher volumes) can usually be maintained provided sufficient pavement structure remains in-place. Efforts continue to be made to improve the overall productivity of these machines by developing longer lasting cutting teeth and reducing equipment downtime.

Sizing

As previously mentioned, the reclaimed asphaltic material should be reduced to an appropriate maximum size through the crushing or milling processes. Based on past projects, this appropriate maximum size appears to be in the 1 1/2- to 2-inch range. Particles of this size seem to be able to break down into their original asphalt and aggregate components when put back through a batch or dryer-drum plant modified for hot recycling. This allows thorough mixing with the additional new materials. Also, existing crushing and milling equipment can readily produce material in this size range while maintaining high production rates and without significant aggregate degradation. In most cases, specifying a maximum size less than 1 1/2 inch is unnecessary; it only increases costs and aggregate degradation. Allowing particles greater than the 2-inch maximum in a hot recycling process is very risky because they may not break down inside the plant. When this happens, the large chunks remain intact in the final mix adversely affecting laydown and performance of the pavement.

Reprocessing

Batch Plants

In a conventional batch plant operation, virgin aggregate is dried and heated in a counterflow dryer, screened into various size fractions, proportioned with hot asphalt cement, and thoroughly mixed. Several attempts have been made to recycle reclaimed asphaltic material directly through the dryer in this type of operation. These attempts have usually resulted in low production rates, excessive smoke emissions, and material buildup problems.

The only technique that has proven successful in recycling through a batch plant is the mixer heat-transfer method. In this method, virgin aggregate is superheated (450°-600°F) in the dryer and transferred to the tower by the hot elevator. The reclaimed asphaltic material, which has been previously reduced to an appropriate size and stockpiled at ambient temperature, is transferred to the weigh hopper in the mixing tower by an auxiliary conveyor system. There it is proportioned with the superheated virgin aggregate. Heat transfer occurs as the two materials are mixed in the pugmill with additional asphalt cement and/or an asphalt softening agent.

Figure 2. Batch plant modified for mixer heat-transfer method.

The mixer heat-transfer method minimizes the possibility of smoke emissions and material buildup problems by not passing the reclaimed asphaltic material through the dryer, hot elevator, and screens. There is some sacrifice of gradation control with this process, but with the lower percentage (50% or less) of reclaimed material that is generally used there has been no problem on past projects in meeting standard gradation requirements for new mixes. Near normal production rates can usually be maintained at the plant using this technique. The percentage of reclaimed asphaltic material that can be used depends on the following factors:

1. The moisture content of the reclaimed asphaltic material.
2. The required temperature of the resultant mix.
3. The temperature to which the aggregate is heated.
4. The stockpile temperature of the reclaimed asphaltic material.

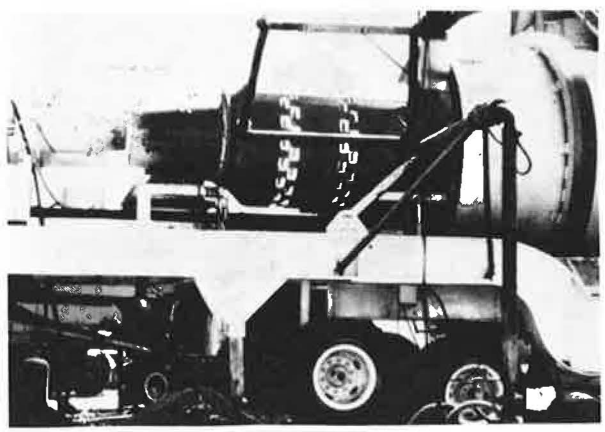
The mixer heat-transfer method was first used on a project in Maplewood, Minnesota, in 1976. Since that time, many projects have been successfully completed using the technique. These projects have generally used up to 50 percent reclaimed asphaltic material. Several plants with baghouse collectors have used the process and no major problems have occurred, but it should be noted that the exhaust gas temperature must be carefully controlled to avoid damaging the bags. The cost to modify a plant to recycle by this method is minimal and such a modification can be made on most existing batch plants in this country.

Dryer - Drum Plants

In a conventional dryer-drum operation, virgin aggregate is proportioned at the cold feed; then it is dried, heated, and mixed with hot asphalt cement in a parallel-flow dryer. Since the aggregate enters at the burner end of the drum, it is immediately exposed to very high temperatures from the flame and hot gases. Early attempts to hot recycle were made through unmodified or only slightly modified dryer-drum plants. Exposing the reclaimed asphaltic material (especially the very fine asphalt particles) to the high temperatures at the burner end of the drum produced very heavy smoke emissions. Despite the emissions problem, satisfactory mixes were produced on most of these early projects. This encouraged several governmental agencies and private companies to continue to investigate the concept of hot recycling through a dryer-drum plant. A considerable amount of effort has been made during the past several years by certain equipment manufacturers to develop modifications for drum mixers which would produce satisfactory mixes, maintain high production rates, and minimize air quality problems. The following sections briefly describe the plant modifications that have proven successful on past projects and are currently being used to hot recycle.

Pyrocone System. This system, developed by the Boeing Construction Equipment Company, controls the heat transfer rate at the burner end of the drum to prevent overheating the reclaimed asphaltic material. The system consists of a cylindrical combustion chamber with a conical heat shield ("Pyrocone") at one end. The unit is installed between the burner and the drum entrance by moving the burner assembly back on the drum frame. The flame volume is contained within the cylindrical chamber where excess air and combustion gases are mixed to produce a lower temperature, air-rich mixture. The excess air flows into the combustion chamber through slots in the chamber wall. The reclaimed asphaltic material enters the drum (usually with some percentage of virgin aggregate) by a single conveyor at the burner end. The materials are gradually heated and blended, additional asphalt cement and/or an asphalt softening are added, and mixing is completed in the remainder of the drum.

Figure 3. Pyrocone system.



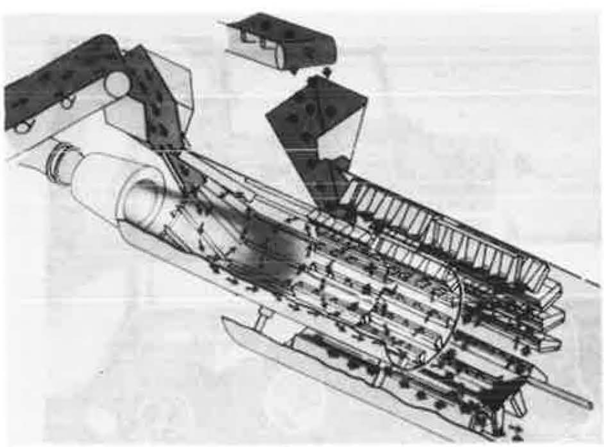
The reduced heating rates produced by this system are the result of the following three interrelated factors:

1. The heat shield ("Pyrocone") reduces direct heat radiation by interrupting the line-of-sight path between the flame volume and the material to be heated.
2. The heat energy entering the drum is more uniformly distributed over the drum cross section.
3. The temperature of the incoming gases is lowered from 2500+ degrees F. to approximately 1200 degrees F.

This system does have the capability of using 100 percent reclaimed asphaltic material, but a more reasonable maximum to expect in order to control smoke emissions is approximately 60 to 70 percent. If conventional (all virgin) mix is to be produced by a plant having this modification, the heat shield ("Pyrocone") can be readily removed.

Drum-in-a-Drum System. The "Drum-in-a-Drum" recycling system was developed by the Iowa Manufacturing Company. With this system, a convenional dryer-drum is modified by moving the burner back from the end of the main drum and inserting a smaller drum. The burner discharges into the upstream end of the smaller drum which extends coaxially into the main drum. The virgin aggregate enters at the burner end of the smaller drum and thus is in direct contact with the flame. The reclaimed asphaltic material enters through the annular space between the outer and inner drums; therefore, it is shielded from direct contact with the flame, but is heated by tumbling against the hot inner drum. The superheated virgin aggregate exits from the downstream end of the inner drum and joins the partially heated reclaimed material. The two materials are then combined with additional new asphalt cement and/or an asphalt softening agent, and the mixing continues throughout the remainder of the main drum.

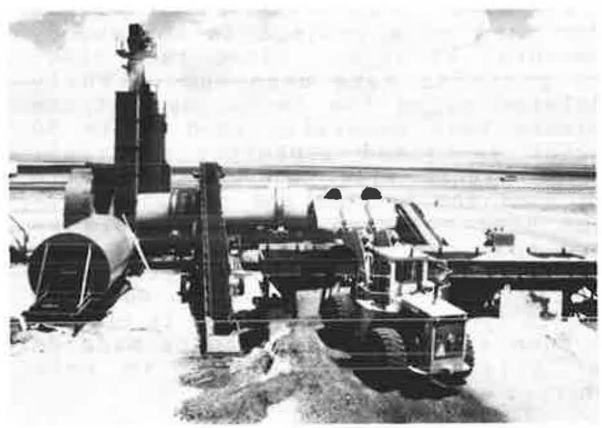
Figure 4. Drum-in-a-drum system.



This system can use a maximum of 50 to 70 percent reclaimed asphaltic material. The required plant modifications are relatively simple and inexpensive, and conventional hot mix can be produced without having to remove the inner drum.

Center-Feed System. In this type of system, virgin aggregate enters at the burner end of the drum while the reclaimed asphaltic material enters near the midpoint (behind the radiation shield that is commonly used in some plants). Flighting in the drum may be modified in order to insure maximum heat transfer to the virgin aggregate. The virgin aggregate will usually be in the 300-500 degree F. range by the time it reaches the midpoint of the drum, while the combustion gases will normally have cooled to 800-1000 degrees F. This provides sufficient heat for mixing with the reclaimed material, but usually not enough to cause overheating and resultant smoke problems. The reclaimed material enters the drum through a series of gates, chutes, or other types of openings that are covered by a metal collar extending around the drum shell. In some cases, additional cooling air may be incorporated at this entry point in order to further reduce temperatures and minimize the possibility of overheating. Additional asphalt cement and/or an asphalt softening agent are added to the combined materials and mixing is completed in the lower half of the drum. This type of system can use a maximum of approximately 60 to 70 percent reclaimed asphaltic material, and it can be readily switched to the production of conventional mixes.

Figure 5. Center-feed system.



The basic concept behind this type of recycling system was originally conceived by Mr. Robert Mendenhall of the Las Vegas Paving Corporation. Mr. Mendenhall developed a "split-feed" system in which crushed asphaltic material was divided into several size fractions and each entered the drum at different points. The coarse material entered at the burner end and the finer fractions entered away from the flame at intermediate points along the length of the drum.

The following equipment manufacturers have developed "center-feed" modifications for dryer-drum plants:

1. Barber-Greene Company ("Dual-Zone Thermodrum")
2. CMI Corporation ("Roto-Cycler")
3. Standard Havens Company ("Cone-flight")
4. Astec Industries, Inc. ("Dual Entry System")

Each of the above described systems ("Pyrocone," "Drum-in-a-Drum," and "Center-Feed") can effectively control smoke emissions while producing hot mixes containing up to 50-70 percent reclaimed asphaltic material. In order to meet current standards for particulate emissions, however, a good wet scrubber or baghouse must be used. This is true whether the plant is producing conventional mixes or mixes containing reclaimed material.

Laydown and Compaction

Conventional equipment and procedures have been used for laying and compacting hot mixes containing various percentages of reclaimed asphaltic material. No unusual problems have been encountered on past projects and normally the mixes containing the reclaimed materials have handled the same as conventional mixes, provided the laydown temperatures have been comparable.

Figure 6. Laying mix containing reclaimed asphaltic material.

Conclusions

The necessary equipment for all phases of hot recycling is currently available. This equipment will no doubt continue to be refined and improved as various highway agencies, contractors, and equipment manufacturers gain additional experience with the recycling concepts. Also, new pieces of recycling equipment (for removing and reprocessing asphalt pavements) with expanded capabilities will probably appear in the coming years as the demand for recycling increases. It can be stated without reservation, however, that the current generation of hot recycling equipment has the capabilities to produce a quality product at competitive production rates while meeting all air quality standards.

DENVER'S METHOD OF URBAN HOT RECYCLING

William E. Smith, Denver Department of Public Works

The street system of the City and County of Denver consists of approximately 1,700 miles of paved and unpaved streets. About 1,640 miles are paved including curb and gutter. Approximately 98% of this mileage consists of asphaltic concrete surfacing. The base course for these streets may include cobblestone, a crushed granite rock, or graded sand and gravel or some deep strength asphalt. The base course is usually related to the type in use during the era in which it was constructed. The streets have various crowns and may slope from 0.5% to 14%; widths may vary from 30 feet to 36 feet (the usual standard). Originally there were streetcar tracks in many of the arterial streets, and these tracks were overlaid over the years. The combination of asphaltic concrete surfacing has varied through the years, but generally consists of a medium soft rock mined from gravel pits along the South Platte River with a Los Angeles Abrasion Test of between 35 and 40. The temperature extremes in Denver range from -20°F. to 110°F., and rainfall is 12 to 14 inches per year. Low level surface oxidation does occur in Denver.

Chip sealing was a common practice until 1973 and almost all residential and collector streets received chip seal treatment every seven to ten years. The chip seal consisted of a Platte River gravel and a RC-800 asphaltic material. Arterial streets did not receive chip seal and were, almost without exception, overlaid with asphaltic concrete. Overlays were conducted every four to five years. Thickness varied from one to two inches. The material generally consisted of a Platte River gravel and, of course, the bitumen equivalent to an AC-10 or 20. Most of the City's streets have a concrete curb and gutter, and in the older areas this has been overlaid many times until there is often only one to three inches of curb remaining. Most of these streets also have high crowns.

Streets to be recycled require more than a cursory review in that quite often the overlays that have occured are a result of subbase failure due to increased loads and volumes of traffic. If this is the case and a determination is made to recycle the pavement, it is essential that an exact or greater pavement section than existed be maintained. On two occasions excess pavement was removed. We found that subbase failure had occured where traffic volumes and weights were high. With these increased volumes and weights it has been necessary for the traffic engineer to remove parking on arterial streets and add traffic lanes adjacent to the curb in order to handle the increased number of vehicles. Failures occured on this curb lane due to water in the flow line, construction, and maintenance that has occured over the years. A joint existed when the Portland cement concrete curb abutted the asphaltic concrete pavement, and this has always been a problem of base failure. As the street was overlaid, the thickness on these edges was tapered to the joint. As a result the pavement thickness is less along the edges. As the surface planing starts it is usually the intent to remove one and a half or two inches adjacent to this curb in order to achieve maximum flow line capacity. This one and a half or two inch removal can be disasterous since the pavement section in the weakest part of the street is reduced. It is, therefore, suggested that if you are looking at a recycling program, pay close attention to the needed pavement section for present day traffic since many of these older streets have been upgraded (overlaid) as failure occured.

In 1979 during the months of March and April, we decided to remove the surface of a major arterial which had extensive patches, numerous chuckholes, and some reflective cracking. Needless to say, this had been a problem all winter so it would have been a very little loss to experiment with the removal and then attempt to overlay when weather permitted. The removal of the top two inches of surface progressed without difficulty, and the rideability of the surface was improved, although the texture of the dry surface created a driver problem in that the rideability of the street was comparable to a cobblestone surface. There were several complaints about the noise and the inability of the drivers to maintain control of their vehicles. The public and media called it a chicken wire texture. The surface was used by the public for approximately two months before the overlay occured, and we had very little difficulty after the first week of complaints. When the overlay started in June, we had trouble with slippage on a high volume bus lane, and it was necessary to change the mix and add some additional tack coat to that particular lane to alleviate the slippage problem.

The previous method for correcting street failures has been to overlay the surface. This has resulted in steep crowns, better pavement sections and a greater cost to replace the street when it was necessary to remove all the curb, gutter and pavement. With limited budgets it is nearly prohibitive to even consider starting at subgrade for rebuilding. We, therefore, have searched for an economical method to maintain a given street in its present condition. With accelerated costs occuring, it was not difficult to set a policy whereby the City would remove one, two or three inches of asphalt and replace the same amount, thereby creating a new surface which offered equal life and better rideability than the surface prior to cold planing. Considering the investment and cost of acquiring the necessary equipment, the cost benefits are very advantageous to recycling, and these will be discussed later.

The City of Denver has a Barber-Greene batch plant rated at 250 tons per hour. There is a bag house for air pollution control and we find that this is very adaptable to hot mix recycling. The recycled material is injected behind the bag house. Thus the quality of mix produced is equal to or better than the virgin mix. One of the problems encountered with the virgin mix was inadequate fines (passing a #200 sieve). By adding the recycled material more fines are introduced. The greater concentration of fines is a result of the grinding procedures which occur during removal. The following gradation depicts the difference between our virgin rock and that of recycled material (See Tables I, II and III).

Table I. A comparison of virgin vs. reclaimed material size.

	% Passing Reclaimed Material	% Passing Virgin Material
1/2"	100.0	100.0
3/8"	93.3	94.5
#4	78.2	77.8
10	58.4	54.0
40	26.9	18.9
80	15.4	7.6
200	9.5	3.9

Table II. Physical characteristics of reclaimed materials.

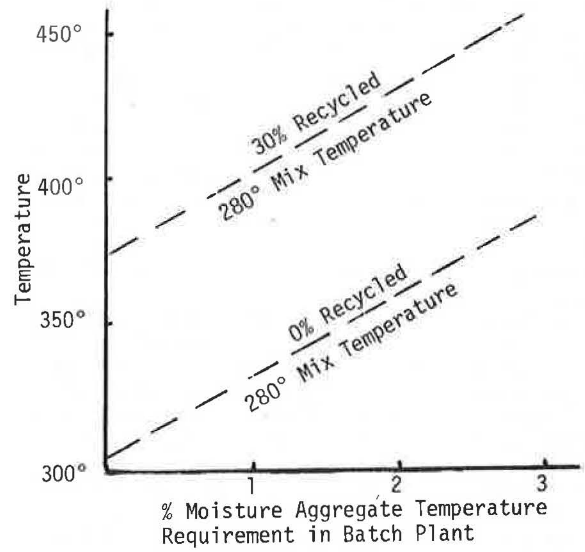
	Reclaimed Material Marshall Method
Lab Density	2.311
Lab Weight	144.1#/cu. ft.
Stability	2,735
Flow	10
Air Voids	3.14%

Table III. Physical characteristics of virgin materials.

	Virgin Mix Marshall Method
Lab Density	2.257
Lab Weight	140.8#/cu. ft.
Stability	1,625
Flow	6
Air Voids	7.50%

It is required that the virgin rock be heated approximately 50°F. to 60°F. above what would be required for non-recycled material, but the resulting temperature at the laydown machine is adequate. The following graph (Figure 1) shows the temperature required for a 280°F. mixture with virgin rock versus 30% recycled mix.

Figure 1. Temperature requirements for reclaimed vs. virgin mixes.



The batch plant is operated by natural gas, which at this point is still the cheapest source of fuel available. We find the stationery batch plant is advantageous from the standpoint of being located in a central point of the City, and since all of the work occurs in Denver, there is no need for a mobile plant.

The first attempt at recycling resulted in the bag house plugging. This was caused by the attempt to place the asphalt to be recycled into the virgin rock before heating and, of course, the heat releasing the cutbacks in the asphalt as well as from evaporation of the bitumen created the problem of particulates which blocked the bag house. We then reverted to placing the recycled material into the drum of heated rock and this resulted in no visible pollution emitting from the exhaust. This, however, limits the amount of material that can be recycled. We heat the rock to approximately 345°F. and then when we add the recycled material it decreases this temperature to about 290°F. It still results in a job site temperature of around 280°F. which is adequate for this mix. There are several things involved in this environmental evaluation, but probably the strongest item is the conservation of both gravel and bitumen. The 30% recycle gives a direct savings on both of these items and results in less mining operations necessary for gravel as well as less processing of oil products. Our addition of 30% recycled material has resulted in a higher bitumen content. We were running as high as 7% on the mixture, and while this exceeds recommended standards, we found that on many local streets where light weight vehicles as well as light volumes of traffic occured this was very advantageous in the life expectancy of the street surface. During this summer's operation, we normally added 5% AC-10 or 20 to the virgin rock, and this has resulted in a six to six and a half percent bitumen content. This will fluctuate, however, depending on the asphaltic content of the recycled material.

Energy savings are closely related to the environment in that we do save the 30% of materials which are recycled. However, there are additional savings from energy which are in the form of transportation. We are able to haul the materials from the planing machine to the batch plant on the return trip of trucks which have delivered hot mix asphalt to areas cold planed the previous day. During this season we have found that it is more beneficial to separate the operation of paving and planing into two separate operations in that breakdowns, delays because of traffic, etc. created more problems and delayed both operations to such an extent that it was more beneficial to run separate operations. This results in an energy tradeoff of removing the material to be recycled against what would be required to mine gravel, crush gravel and deliver gravel to the batch plant. Needless to say, the energy required to remove the material to be recycled is much less.

The cost for cold planing two inches of material from Denver's existing streets was 88¢ per square yard in 1979. The estimated value of the material removed was $1.60 per square yard. With the increase in cost of bitumen, gravel and transportation, it is obvious to me that we must do more recycling. It is simply a matter of what type of recycling is most beneficial from both the cost standpoint and final product achieved. One must examine this from the needs of their particular entity. If this need is for overlay, then I feel strongly that hot mix recycling is most advantageous. If it is for the base course, then perhaps cold mixing is more beneficial. Whatever the results are, recycling is certainly necessary in our limited budget and rising costs.

RURAL HOT MIX RECYCLING

Robert A. Welke, P.E.
Michigan Department of Transportation

Hot recycling is the transporting of salvaged existing asphalt pavement from its original location to a central asphalt plant site for processing. Rural roadways that are recycled may present different problems and needs than urban projects. Generally, with the type of asphalt pavement encountered in rural projects, technologists need to consider the variability of the salvaged material that is designed into a recycled mixture. During the past four years much has been done to develop recycled asphalt mix design procedures. These procedures are being time tested and will, by the nature of the technology, be revised continuously. Rural roads that are recycled may, due to their length and lower traffic volumes, dictate lower unit cost designs. Recently developed equipment allows the removal of the total existing pavement or variable thicknesses of the upper pavement surface for recycling. The Michigan Department of Transportation has hot recycled several rural roadway projects during the past three years. Two typical rural recycling projects--one using drum mix recycling, the other using batch plant recycling--are discussed, and information and data on cost and energy conservation are presented.

Most Michigan trunkline flexible pavements are asphaltic concrete, constructed of high quality aggregates. Due to heavy traffic volumes with a large percentage commercial on the rural roads it is necessary to design all pavement sections for a high level of serviceability. To provide the public with the best possible roadway surfaces, it is apparent that we must develop an alternate to overlaying of existing pavements. This alternate is asphalt recycling.

The time of going to the 'back forty' and opening up a gravel pit is over in many parts of the country. Zoning laws and land use controls have made the availability of low cost aggregates a thing of the past. In Michigan it is not uncommon to haul high quality aggregates more than 161 km (100 miles) from their source to an asphalt plant site. It is apparent that we must conserve this natural resource if we are going to control product cost.

During 1979, the cost of asphalt cement increased 35 percent. The National Asphalt Paving Association has forecast that asphalt and fuel oil costs will increase 46 percent during 1980. Presently, about 45 percent of our asphalt comes from imported crude oil. With world political conditions as unreliable as they are, we may see higher-than-forecast asphalt prices or a reduction in supply of asphalt material.

Decreasing natural resources and large increased costs of asphalt have not diminished the need to maintain and improve our asphalt pavements. Both public and private organizations are feeling the pinch of ever increasing costs of asphalt paving and the continued need to extend or improve existing asphalt surfaces.

The Michigan Department of Transportation has 4,802 km (2,984 miles) of flexible pavement roads and 6,524 km (4,054 miles) of asphalt overlayed rigid pavement on the state trunkline system. In addition, most of the 128,748 km (80,000 miles) of the county road systems are asphalt. With the large increase in construction costs during the past few years it is difficult to keep up with the needs. Asphalt recycling has become a method that has the most potential to improve asphalt pavements while controlling costs and reducing energy requirements.

It is said that necessity is the mother of invention. Although asphalt recycling has been around for many years, very little was done to foster it until after the 1973 oil embargo. In Michigan we started cold in-place recycling of existing asphalt pavements in 1970. But the interest and monies for this work did not increase until 1974. Since that time, we have cold recycled several hundred lane-kilometers of asphalt pavement and hot mix recycled over 362,874 metric tons (400,000 tons) of salvaged asphalt.

From an engineering point of view, we are at the advent of considering asphalt recycling as a standard practice. In fact, in the Michigan Department of Transportation, most projects that are scheduled for resurfacing are evaluated for possible recycling. We have 20 projects scheduled for hot recycling and several for cold recycling this year.

It has been common practice in the past to pile layer upon layer of new asphalt mix on pavements that were distressed. This would improve the pavement structure and ride, but would not eliminate the reflective cracking problem, in which cracks in the old surface reappear or 'reflect' in the new layer. In a few years the resurfacing was in the same condition as the original asphalt pavement. Many times resurfacing will not solve the problem, but only add to it. Recycling of existing asphalt allows for the breaking up of the cracked pavement, thus reducing the potential of reflective cracking in the new surface.

It is apparent that besides conserving energy, materials, and lowering construction costs, recycling can improve the pavement structure. It also can extend pavement longevity. We have enough experience to determine that asphalt is truly recyclable and at a cost that is less than 100 percent virgin mixes. Early test results have indicated that the aging or hardening of the asphalt binder in hot recycled mixtures is slowed in relation to conventional mixes. If this is true, the service life of a recycled pavement may be longer.

During the past several years much has been done to develop recycled asphalt mix design procedures. These procedures are being time-tested and will, by the nature of the technology, be revised continuously. We have developed computer programs for recycled asphalt mix designs to aid the practitioner in handling the increased number of variables encountered.

Project Design

Project History

After a potential project has been chosen, it is important to review the past construction records. It is essential to know the history of construction, what materials were used, and the cross-section. If the roadway has a widely varied history and was constructed in a patchwork manner, it might be best not to consider it for recycling. Uniformity of materials and cross-section make for a more uniform recycled mix. Also, by checking past construction records one can possibly determine if tars or extensive amounts of liquid asphalts were used. If these materials are present in large amounts, again it may be best not to hot recycle because of potential air quality problems.

Coring

Coring the existing roadway is the next process. A certain number of cores are needed in order to obtain material for testing. Usually 10 to 20 cores are sufficient.

Sample Aggregate Base

When cold milling the existing pavement it is our experience that approximately 1.3 cm (1/2 in.) of aggregate base will be included with the salvaged pavement. A sample of the aggregate base is needed to determine if there are any large stones present (greater than 3.2 cm or 1-1/4 in.). If large stones are present this could cause paving problems. Crushing, scalping to remove oversize material, or not considering the project for hot recycling are the solutions if large stones are present. Also, if the pavement is directly on clay, it will cause the problem of having clay balls in the recycled mix. The only solution is to cold mill partial depth or not recycle.

Measure Thickness of Cores

This is valuable information for cold milling contractors and for design of the recycled mixture. Often the existing pavement will consist of various thicknesses of wearing, leveling, and base courses that have different properties and each requires consideration.

Extraction and Abson Recovery

The next process is to run an extraction analysis of the existing pavement. This will give vital information concerning gradation and asphalt content.

The Abson Recovery process will give information as to the hardness of the existing asphalt binder. The first step is to take the effluent from the extraction and centrifuge out the fine dust particles. The presence of dust will make the asphalt cement appear harder than it really is. The next step is to distill off the solvent (usually trichlorethylene). The last step is to run a penetration of the salvaged asphalt cement at 25 C (75 F).

Tabulate Results

Once the results are known, they should be tabulated, averaged, and the standard deviation calculated for all sieves, the asphalt content, and the recovered penetration.

Mix Design

In order to design any bituminous mixture it is important to know the location, the environment, and the needs. Traffic volumes and loading, the climate, and the supporting base materials are the most important factors; however, there may be other considerations unique to a particular highway.

Rejuvenate Old Asphalt

In order to produce a suitable recycled mix it is paramount to have the asphalt binder at the proper consistency. We at MDOT have developed a chart (Fig. 1) which aids in making the proper decision as to what type and how much rejuvenating material is needed. Note the left and right y-axes. The left y-axis represents the viscosity of the material at 25 C (77 F) and the right y-axis represents penetration at 25 C (77 F). There is a very strong correlation between viscosity and penetration, thus, corresponding values can be substituted freely.

The first thing one does when using this chart is to shade-in the area of desired consistency of the resultant recycled mixture. In this case we are designing the recycled mix to be similar to a new 85-100 penetration grade asphalt mixture. Next the recovered penetration (or viscosity) of the reclaimed pavement is plotted (38 in this case) on the left y-axis. On the right y-axis the penetration (or viscosity) of the rejuvenating agent is plotted (in this case a 250 penetration asphalt cement). Next the two points are connected by a line and where the line intersects the shaded area is the desired blending index in percent (42 to 48).

From knowing the desired blending index one can use this value to compute the percent of salvaged material to be used in the recycled mixture. The percent salvaged material to be used is as follows:

$$S = 100 - \frac{AC \times BI}{AD}$$

Where:

S = salvaged material, percent
AC = asphalt content of salvaged material, percent
BI = blending index, percent
AD = asphalt demand of recycled mix, percent

Example:

AC = 5.2, BI = 55, AD = 5.8

$$S = 100 - \frac{5.2 \times 55}{5.8} = 100 - 49.4 = 50.6 \text{ percent}$$

Thus, for this example a 50 percent salvaged - 50 percent virgin mixture would be desirable. If one wanted to go to a higher percentage of salvaged material (lower blending index) then a softer rejuvenating material would be needed.

Gradation Analysis

The next design process is to analyze the gradation of the reclaimed material and decide what the gradation of the new aggregate should be. From our experience, cold milling does not significantly change the gradation of the reclaimed pavement except for the 0.075 mm (No. 200) sieve. It generally raises the material passing the 0.075 mm (No. 200) sieve by approximately 3 percent.

Sample Stockpiles

At this time it is assumed that the contract has been let, cold planing has started, and the sources of virgin aggregates are available. Thus, a representative sample of each can be obtained for mix design.

Extraction and Abson Recovery

Again, an extraction must be run--this time on the cold milled material. The increase in passing 0.075 mm (P200) should be noted along with the reduction in the asphalt content because of inclusion of the aggregate base.

From the Abson process, the recovered penetration of the cold milled material should match closely with the values from the cores.

Marshall Mix Design

Conventional Marshall Mix Design procedures and design criteria are sufficient. The aggregates and reclaimed pavement are heated to 140 C (285 F) and are mixed and compacted. It should be noted that the stabilities of recycled mixes are quite high because the milling process creates more crushed material.

Drum Mix Recycling Project

Construction

The Michigan Department of Transportation completed its first asphalt hot mix recycling test section in 1977. Based on the experience gained from this project and information from recycling projects around the country, it was decided to construct two large rural hot mix recycling projects in 1978. By specification, one project would be recycled by the drum mix method and the other the heat-transfer method requiring a batch plant.

The location of the 11.6-km (7.2 mile) recycled portion of this project was on M 57 between M 66 and Berridge Rd in Montcalm County, east of Greenville. The work consisted of removal and reduction of the existing 6.7-m (22 ft) bituminous pavement (two 3.7-m, or 12-ft lanes and a 0.9-m, or 3-ft paved shoulder) at 179 kg/m^2 (330 lb/sq yd). Also included in another portion of the project was a conventional bituminous resurfacing.

Test Results

Large variations in the asphalt content and gradation test results are undesirable when producing a high quality bituminous paving material. However, it was anticipated, even before the project had started, that there would be more fluctuations in the test results than found in conventional mixes. The reason for this was the added variable of the salvaged material. Any of the following factors can cause this added variability:

1) variability in original bituminous mix,
2) variable thickness of different courses (wearing, leveling, or binder),
3) different construction histories (e.g., one area has had a resurfacing with a different composition of mix while another area has not),
4) fluctuations in depth of aggregate base removed with the bituminous pavement.

Existing bituminous pavements that have wide variances in any of the first three factors should not be considered for hot mix recycling for producing a wearing course. M 57 was chosen as a suitable project for a recycled wearing course because of its uniformity. Except for a 0.8-km (1/2 mile) section that received a 5-cm (2 in.) resurfacing, the material was uniform throughout the 11.6-km (7.2 mile) project. Factor number four was considered to be the most significant on this project for producing variability in the salvaged material.

As mentioned previously, approximately 1.3 cm (1/2 in.) of aggregate base was removed along with the existing pavement in order to assure a good bond for the recycled mix. The following table shows the asphalt content of the salvaged material when various depths of aggregate base are included (assuming a 4.8 percent asphalt content in salvaged mat and a 7.6-cm (3 in.) pavement thickness).

Quantity of Aggregate Base Salvaged, cm	Asphalt Content, percent
0	4.80
0.6 (1/4 in.)	4.43
1.3 (1/2 in.)	4.11
1.9 (3/4 in.)	3.84
2.5 (1 in.)	3.60

Thus, one can see that a minor fluctuation in the cold milling operation can cause a substantial fluctuation in the asphalt content in the salvaged material.

The average asphalt content for the entire project was 5.06 percent for the plant and 4.99 percent for the laboratory. At the beginning of the job, 5.4 percent was the target; however, the amount of material passing the 0.075-mm (No. 200) sieve was significantly higher in the actual mix than in the mix design. The reason the passing 0.075 mm (P200) was higher and the combined asphalt content lower in the mix design was because more of the aggregate base was removed than had been expected. The laboratory averaged 6.78 percent passing 0.075 mm (P200); plant values are often inaccurate due to less sophisticated equipment. The mix design was based on 5.8 percent passing 0.075 mm (P200). A mix design rule of thumb is that for an increase of 1 percent in the material passing the 0.075-mm sieve (P200), the asphalt content should drop 0.3 percent.

Cores were taken from the newly compacted pavement and the air voids were found to be 3.6 percent at 5.2 percent asphalt cement. Air voids will become less with time as traffic further compacts the pavement. Experience has shown that 3.0 percent is the desired air voids after traffic has had a chance to compact the pavement. However, 3.6 percent air voids for newly compacted pavement is low; thus, asphalt content around 5 percent did not seem excessively low. Appearance of the mix was good; however, the percentage of new asphalt added was increased (0.1 percent) to 2.8 percent for a 60-40 percent salvaged-virgin mix in order to keep the combined asphalt content from dropping too low. For a 70-30 mix, 2.3 percent asphalt cement was added; for an 80-20 mix, 1.9 percent asphalt was added; and for a 90-10 mix, 1.3 percent asphalt cement was added. The combined asphalt content was approximately 5 percent for all mixes.

In order to analyze the variability found in the control charts, a comparison with conventional mix variability is necessary. Standard deviation is used as the indicator of variability. Table I compares the variabilities for 10 end product (conventional wearing courses) projects done over the past three years in Michigan with the variabilities within the M 57 project.

Standard deviations of asphalt contents were higher for the recycled project than for conventional mixes. This was expected due to the added variability of the salvaged asphalt cement. Although variability is higher it is believed that the effects on the wearing course will be insignificant. It should also be noted that a contributing factor to the 0.37 plant asphalt standard deviation was the presence of moisture. Drum mix plants do not fully dry the aggregate, and moisture in the mix appears to be asphalt cement in plant extraction results. Although moisture corrections were used on this project, the added variable undoubtedly increased the standard deviation for the plant results.

In analyzing the variability of the aggregate gradations, it must be remembered that a change in the mix proportion of salvaged and virgin materials caused a small change in the percent passing the various sieves, thus increasing total job variability. Even so, for the 0.075-mm (No. 200) and 0.6-mm (No. 30) sieves the standard deviation was slightly lower than average, and for the 2.36-mm (No. 8) and 9.5-mm (3/8 in.) sieves it was slightly higher. It was somewhat unexpected that the variability for the aggregate gradations proved to be comparable to that of a conventional mix. It is felt that the reason for this was the fact that the aggregate base, the salvaged material, and the virgin material all have similar gradations.

Recovered penetrations (indicator of viscosity) of recycled asphalt cement from laboratory extractions varied depending upon the percentage of salvaged and virgin used (Table II).

TABLE I

Asphalt Content and Gradation Analysis	Standard Deviations For 10 Projects			Standard Deviation For M 57 Recycle
	Avg.	High	Low	
Plant asphalt content	0.20	0.29	0.14	0.37
Lab asphalt content	0.21	0.30	0.12	0.29
Plant passing 0.075 mm (P200)	0.69	0.96	0.38	0.52
Lab passing 0.075 mm (P200)	0.76	1.14	0.31	0.51
Plant passing 0.6 mm (P30)	2.1	4.3	0.9	1.9
Lab passing 0.6 mm (P30)	2.2	3.1	1.1	1.6
Plant passing 2.36 mm (P8)	2.3	3.7	1.6	3.1
Lab passing 2.36 mm (P8)	2.3	2.9	1.3	2.7
Plant passing 9.5 mm (P3/8)	2.3	3.0	1.8	3.3
Lab passing 9.5 mm (P3/8)	2.6	4.3	1.7	3.0

It should be noted that all the variability of test results is not caused by variation in the mix, but also by sampling and testing errors. Although it is being studied at present, we are not able to separate the mix variation from sampling and testing errors. Thus, overall variability of test results is the only available indicator of mix variation.

As expected the higher the percentage of salvaged material used, the lower the recovered penetration (the higher the viscosity). Recovered penetrations in the 50's would be comparable to a typical recovery of a new 85-100 penetration grade pavement where values in the 70's would represent a new 120-150 pavement. Thus, the 80-20 and 70-30

TABLE II

Recovered Penetration	Original Pavement From Cores	Recycled Mix, Salvaged Virgin, percent			
		90-10	80-20	70-30	60-40
Average	38.4	41.7	53.9	55.0	68.2
High	45	45	83	59	83
Low	28	36	42	48	55
No. of Samples	7	4	11	11	9

mixes would seem to be similar to a new 120-150 mix. Analysis of the old pavement showed an average recovery of 38 which indicates that the original asphalt cement still had some life in it. Recovered penetrations below 25 are thought to be indicators of a crack susceptible material. It is common to find badly cracked areas with recovered penetrations in the teens. Although recovered penetrations are not a fail-safe method of predicting cracking susceptibility, they are an indicator. Thus it is felt that 200-250 penetration grade asphalt sufficiently rejuvenated the old asphalt cement to the viscosity of a new cement, except for the 90-10 mix.

There is a widely accepted theory that some of the old hardened asphalt that was absorbed into the aggregate does not become part of the effective asphalt in a recycled mix. Thus, the recovered penetrations in a recycled mix are lower and are not true indicators as to the hardness of the effective asphalt cement. It is felt that a recycled mix may have a greater service life than the recovered penetrations indicate.

Moistures in the mix and stockpiles were monitored. Moisture in the virgin stockpile averaged 2.5 percent on a dry basis, and 2.0 percent in the salvaged pile. Anywhere from 1 to 3 percent water was added on the cold feed belt; however, this moisture had no chance to be absorbed into the stone and evaporated quickly upon entering the drum. Moisture in the mix varied with temperature. At 132 C (270 F), 0.05 percent was in the mix, and at 116 C (240 F), 0.15 percent moisture was measured.

Approximately two months after construction, wet friction coefficients of the pavement were measured at 64 km/hr (40 mph) in accordance with ASTM E274. The average value was 0.54 with a high of 0.57 and a low of 0.49. The statewide average friction coefficient for initial construction is 0.51.

Air Quality

Particulate emissions were measured by Department personnel in order to determine if the plant complied with Federal and Michigan standards. Federal standards require that particulate matter shall not exceed 0.04 gr/DSCF (grams per dry standard cubic foot) and the plume shall not exceed 20 percent opacity. Michigan standards require 48 gm/1000^3 (0.30 lb/1,000 cu ft) of gas, approximately equivalent to 0.15 gr/DSCF, and the plume shall not exceed 20 percent opacity.

Table III shows the particulate emissions measured for this project.

TABLE III

Date of Sample	Mix Ratio Salvaged-Virgin	Particulate Emissions gr/DSCF (EPA Method 5)
August 1, 1978	80-20	0.20
August 3, 1978 - #1	90-10	0.21
August 3, 1978 - #2	90-10	0.20
August 4, 1978	80-20	0.19
August 10, 1978 - #1	70-30	0.11
August 10, 1978 - #2	60-40	0.09

All six tests were above the 0.04 Federal requirement but two of the six were below the 0.15 Michigan requirement.

There was no one available trained in measuring opacity; however, at 60-40 salvaged-virgin and 70-30, the plume of the stack appeared as steam only. At 80-20 a light blue smoke appeared and at 90-10 it became heavy.

Energy-Resource Savings

It is calculated that 719,228 l (190,000 gal) of asphalt cement and 14, 152 metric tons (15,600 tons) of aggregate were recycled on this project. Use of the drum mixer and low mix temperatures saved an estimated 75,708 l (20,000 gal) of dryer fuel oil. It is also calculated that approximately 4,808 metric tons (5,300 tons) of shoulder material were saved (because removal of old pavement the top 7.6 cm (3 in.) of shoulder material was not paved over but bladed over to the new edge of pavement). Quantities are not known, but it is felt that a considerable amount of fuel was saved by recycling the aggregate from the existing roadway. New aggregate had to be hauled 24 km (15 miles) one way to the plant site where the salvaged material haul was from 0 to 9.7 km (6 miles).

Costs

The bid prices for the various items of work were as follows:

Remove, transport, and crush bituminous pavement (4 in. or less)
  $ 1.79/m^2 ($1.50/sq yd)
Remove, transport, and crush bituminous pavement (more than 4 in.)
  $ 2.09/m^2 ($1.75/sq yd)
Aggregate 20AA
  $ 4.96/metric ton ($4.50/ton)
Asphalt cement
  $104.72/metric ton ($95.00/ton)
Recycling bituminous material
  $ 7.94/metric ton ($7.20/ton)

The final quantities varied somewhat from the estimated quantities. Overall, it cost $18.43/metric ton ($16.72/ton) for the entire recycling process. This compares very favorably to the 4.12 wearing course price of $22.27/metric ton ($20.20/ton) and leveling course price of $20.89/metric ton ($18.95/ton) for work elsewhere on the project.

The cost for 90-10 ratios of salvaged-virgin was not significantly different from the cost of a 60-40 ratio $18.42 versus 18.46/metric ton, respectively ($16.71 versus $16.75/ton). The cost of rotomilling on this project was relatively high, $9.71/metric ton ($8.81/ton) of salvaged material. On the I 94 project, the rotomilling cost was $7.28/metric ton ($6.60/ton); however, the average thickness of the pavement was greater (15.2 cm, or 6 in. versus 7.6 cm, or 3 in.). As mentioned previously, approximately 4,808 metric tons (5,300 tons) of shoulder material was saved. At

$3.86/metric ton ($3.50/ton) this would amount to a savings of approximately $18,500.

Batch Plant Recycling Project

Because of the interest in investigating the feasibility of heat transfer type hot mix recycling methods, the Michigan Department of Transportation let a project in June 1978 for hot mix recycling using a batch plant. The Department felt that the experience gained in trying this concept, along with the above drum mix recycling project, would help develop the expertise needed to further the art of hot mix recycling.

With the excellent results obtained on the Maplewood, Minnesota batch plant recycling project (1), Michigan felt it was feasible to let a similar recycling job. A 4-km (2.5 mile) section of eastbound I 94 in Berrien County (LaPorte Rd to US 12) was selected because of the excessive fatigue cracking in the existing pavement. Another reason for selecting this project was that this area of the state has a very limited supply of new aggregates which made the recycling more feasible and somewhat more economical. With these two conditions, the recycling offered the best viable design for this section of I 94 with an ADT of 19,000. The other option of resurfacing with 5 to 7.6 cm (2 to 3 in.) of bituminous concrete would have extended the pavement life only a few years before the cracking in the existing surface would have reflected and resulted in the same condition that was faced at the onset.

A design was selected using a 50-50 blend of reclaimed versus virgin material. Because of the feeling of Department personnel that the existing aggregate base was contributing to the pavement failure, it was decided to utilize this aggregate for the virgin portion of the recycled mixture. The existing pavement consisted of a 12.7 cm (5 in.) thickness, composed of binder, leveling, and wearing courses. The plans called for removing the existing pavement and reducing it to 95 percent passing the 50-mm (2 in.) sieve by either rotary reduction or plant crushing. The virgin portion was obtained from removing 15.2 cm (6 in.) of the existing aggregate base course.

The recycled mix was to be placed 25.4 cm (10 in.) thick in a minimum of three lifts and resurfaced with 70.5 kg/m^2 (130 lb/sq yd) of bituminous concrete leveling course 25A, 65.1 kg/m^2 (120 lb/sq yd) of bituminous concrete wearing course Type C, and 54.3 kg/m^2 (100 lb/sq yd) of Open Graded Asphalt Friction Course. The Department opted for the more conservative approach using the recycled base course on the first project because of the high traffic volumes (ADT of 19,000 and the measured percent commercial of 24 percent).

Construction

The recycling contract was awarded to Rieth-Riley Construction Co., of Battle Creek, Michigan. They moved their 2,948-kg (6,500 lb) H & B portable batch plant to a site adjacent to the project. For this project, the Department allowed the contractor use of limited access right-of-way, permitting him to go through openings in the right-of-way fence. Rieth-Riley used this option and located their plant on the north end of the project with access to the freeway. The existing 12.7-cm (5 in.) pavement was removed with single pass of a CMI rotomill. The rotomilling in a single-pass operation was quite surprising considering our experience on previous freeway recycling that required two passes of the machine for similar pavement thickness. The single pass gave us a very uniformly graded material which alleviated any separate stockpiling or blending of the reclaimed pavement. There was also some concern of possible problems that could be encountered because of the various aggregates used in the original construction and the later widening and resurfacing. The original pavement and the widening used natural aggregates, but the resurfacing utilized blast furnace slag in the wearing course. The possible problem of variations in the asphalt content of the different pavement layers were eliminated with the single-pass operation of the rotomill. The contractor used a CMI Trimmer to remove the existing aggregate base. The 15.2-cm (6 in.) base was easily removed in a single pass and transported to the plant site.

The recycling process consisted of drying the aggregate base and superheating it to a temperature of 316 to 343 C (600 to 650 F) so that when the ambient temperature reclaimed pavement is added in the 50-50 blend, the resultant temperature of the recycled mixture is in the range of 93 to 138 C (200 to 280 F). The only modification needed on the existing plant was to devise a method for feeding the reclaimed pavement to the weigh hopper. Rieth-Riley elected to feed the reclaimed material by means of a conveyor belt to an opening in the weigh hopper. The belt was controlled by an interlocking system tied to the plant scales and controls which ensured the uniform proportioning.

A recommendation also stated in the special provision was that the contractor cover the stockpile of reclaimed bituminous material to minimize variations in the moisture content. The reduction in the moisture content in the reclaimed material results in a fuel savings with the lowered required new aggregate temperatures. Rieth-Riley not only tarped the salvaged stockpile, they elected to also tarp the virgin material so that more complete fuel savings could be realized.

The recycled mixture consisted of 49 percent reclaimed pavement, 48.8 percent virgin aggregate, and 2.2 percent 200-250 penetration grade asphalt cement. The contractor superheated the virgin aggregate (salvaged existing aggregate base) to 316 C (600 F) and deposited it in the hot bins without any oversize screening or sizing of the aggregate. The superheated aggregate was then fed into the weigh hopper where the reclaimed material was added to begin the heat transfer process. The next step was depositing the combined aggregate and reclaimed in the pugmill and mixing for an actual dry mix time of 10 seconds. The 'actual mix time' means a 10-second mixing period after the aggregate and reclaimed material are completely charged into the pugmill.

After the dry mixing period, the asphalt cement was added and mixed for a period of 30 seconds and then transferred to a 90.7 metric ton (100 ton) surge bin for the completion of the heat transfer prior to hauling to the paving site. The recycled mix was then placed and compacted with conventional paving equipment. A mix temperature of 127 C (260 F) was selected, and since density was successfully obtained, and a mixture that proved workable resulted, that temperature was used for the entire project.

Later, during the construction, the proportions were changed to increase the reclaimed aggregate to 55 percent. Even with the increased proportion, there was no apparent problem encountered in producing an acceptable mixture. Although there were neither stack emissions nor opacity tests conducted, the stack never showed any visibly excessive pollution. On all future recycling projects, the Department is requiring the contractor to provide the necessary scaffolding for the monitoring of the stack emissions.

Test Results

Marshall stabilities of 9,146N and 10,885N (2,056 and 2,447 lb) flows of 12.5 and 13.5, and V.M.A. of 15.1 is well within the range of acceptable results for high traffic volume pavement. The air voids of 2.2 percent are a little lower than ideal, but considering that the recycled base would be covered with leveling, wearing, and open graded surfaces, it was quite acceptable. If the recycled material was intended as a wearing course, the selection of the virgin material would have become more critical. We would have selected an aggregate that would result in 3 to 5 percent air voids in the surface course of the recycled.

Energy Resource Savings and Cost

We realized complete resource savings on using the existing pavement and aggregate base for our recycled mix. There was no need to use new aggregate in the recycled base, which in this area of the state is quite desirable because of the absence of quality aggregates. There was also a savings of asphalt cement with the reduction of 2.5 percent when compared with a conventional base course using all virgin aggregate. On this project approximately 31,298 metric tons (34,500 tons) of new aggregate and 772,224 l (204,000 gal) of asphalt cement were saved. The removed bituminous surfaces equate to 15,703 metric tons (17,310 tons) and the removed aggregate base equals 9,182 metric tons (10,121 tons); therefore, the costs of removing the materials would be \$7.28 and 2.98/metric ton, respectively (\$6.60 and 2.70/ton), based on removal contract prices of \$1.79/m^2 for 12.7-cm (\$1.50/sq yd for 5 in.) bituminous surface and \$0.74 for removing 15.2 cm (6 in.) of aggregate material.

The following is the determination of the cost per ton of recycling the mixture:

Salvaged bituminous
    \$ 7.28/metric ton x 0.50 x 0.978 =
        \$ 3.56 (\$ 3,23/ton)
Salvaged aggregate
    \$ 2.98/metric ton x 0.50 x 0.978 =
        \$ 1.46 (\$ 1.30/ton)
Asphalt cement
    \$104.72/metric ton x 0.022 =
        \$ 2.30 (\$ 2.09/ton)
Recycling
    \$ 9.16/metric ton =
        \$ 9.16 (\$ 8.31/ton)
                Total per metric ton =
        \$16.48 (\$14.93/ton)

This compares with the approximately \$17.64/metric ton (\$16.00/ton) that new bituminous base would have cost.

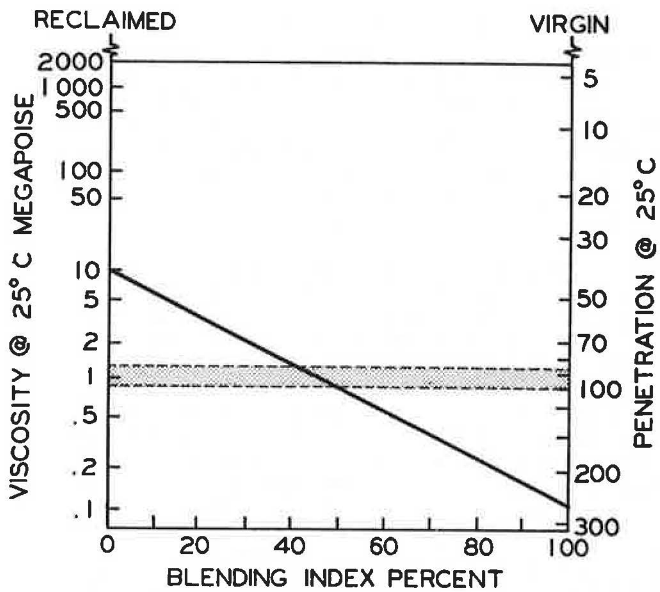
Since 1978, when these two large rural hot mix recycling projects were completed the Department has constructed several more asphalt recycling projects. Using the experience gained from the early projects the Department has generally reduced the salvage to virgin aggregate ratios to a nominal 50-50 percent. This change was dictated by the need to reduce the possibility of stack emissions to within allowable limits and provide sufficient new high penetration asphalt to flux the existing binder in the salvaged material.

During 1979, 18.2 km (11.3 miles) of eastbound I 94 was recycled similar to the project completed in 1978. The later project was constructed with 25.4 cm (10 in.) of recycled asphalt material and 2.5 cm (1 in.) of Open Graded Asphalt Friction Course. The 100 percent virgin leveling and wearing courses were eliminated. This reduction in pavement thickness and costs was prompted by the demonstrated high quality of asphalt recycled mixtures and our confidence in using the material for wearing courses.

References

1. "State-of-the-Art: Hot Recycling," National Asphalt Paving Association, May 1977.

Figure 1. Rejuvenating material chart.



AIR POLLUTION CONTROL FOR ASPHALT PAVEMENT RECYCLING

Robert J. Mauel, P.E.,

For the past eight years I have worked in air pollution control with the goal of improving our environment, so the potential ecological benefits from recycling asphalt pavements greatly appeals to me. When I weigh the savings to be realized in raw materials and in transportation costs, and the elimination of the problem of disposing of old pavement, I can't help but be enthusiastic about the recycling concept.

Because of the ecological benefits, I was tempted to agree when some contractors and highway department personnel suggested that these benefits be allowed to offset the potential increase in air pollution from the recycling process. The legal structure involved, however, does not provide for consideration of offsets of this type. Federal regulations and most, if not all, state and local regulations require literal compliance with the standards they establish. Any departure from the standards involves a clearly defined legal process, which would require extensive hearings with a limited probability of the proposed changes being accepted. It appears that the only practical approach is the development and improvement of the recycling process until it is consistently capable of meeting established air pollution control codes.

Throughout this seminar you have been hearing of the progress made toward perfecting the recycling process. Most major manufacturers of asphalt concrete plants have been experimenting with redesigns and modifications with considerable success in obtaining quality asphalt pavement using recycled materials. In studying these redesigns from the air pollution control standpoint, I am encouraged to find that the process changes also lend themselves to controlling the excessive emissions noted when recycling was first attempted. To be specific, methods are being used to isolate the flame and radiation zone from the recycled materials, which in turn allows early injection of the asphalt. These methods not only promote proper coating of the mix but also alleviate the emissions caused by burned asphalt and absorb the fines that would otherwise be emitted to the atmosphere. It appears that the better the separation of the flame and radiation zone from the recycled materials and the earlier the injection of the new asphalt coating material, the better the quality of the recycled product and the lesser the generation of contaminant emissions.

It is probably fair to assume that all drum mix plants have been manufactured since June 11, 1973, which makes them subject to the Federal New Source Performance Standards (NSPS). It also is probable that most, if not all, state air pollution control agencies accept the NSPS as being best available control technology (BACT) when evaluating permit applications for asphalt concrete plants. Therefore, we should be able to base our air pollution control consideraton primarily on compliance with the NSPS.

To summarize, the NSPS for asphalt concrete plants establishes two basic limitations. First, gaseous emissions from the facility shall not contain particulate matter in excess of 0.04 grains per dry standard cubic foot and, seocnd, emissions shall ot exhibit 20% opacity or greater.

To date some plants have been successful in meeting the NSPS limitations, but usually at the expense of considerably reduced production rates. Even than, it appears that consistent compliance with the NSPS is questionable, although I know of firms that are running their plants at or near normal capacity with relatively consistent compliance with air pollution control standards. It is interesting to note that the firms I have in mind do not necessarily use the same approach for meeting NSPS. Although one firm made several equipment changes simultaneously which could have affected emissions, it attributes it success to reworking of the venturi. The firm installed a guage to measure air flow and now is able to accurately adjust the variable throat venturi for various moisture conditions.

Another firm attributes its success to a process change although the change was not made entirely for air pollution control purposes. One of the motives was to increase the temperature of the mix to 260°-270°F so that it wouldn't clog the hot elevator. To do so, they lowered the slope of the drum and increased production to the maximum.

They found the procedure intensified the veil, which alleviated the blue smoke that had been their major air pollution control problem.

Until consistent compliance is achieved, air pollution control agencies probably will be reluctant to grant permits for other than experimental recycling projects. I am certain that the problems being experienced can be overcome and that the NSPS can be achieved, but I hesitate to predict whether it will be by process modification or by the addition of air pollution control equipment. As an engineer, I hope that the problem is solved at the source by a process change.

In the past, in issuing permits for asphalt concrete plants, we mainly have concerned ourselves with control of particulate emissions. With the increased use of fuel oil in lieu of the once plentiful natural gas, sulfur dioxide emissions are becoming a matter of concern.

We now face the problem of determining best available control technology (BACT) for controlling sulfur dioxide emissions from hot mix plants. In Texas, our approach has been based on the precedent we established by determining that the application of BACT for boilers does not require the installation of abatement devices if the sulfur content of the fuel oil to be fired does not exceed 0.7% by weight. In the interest of consistency, therefore, we consider BACT applied to the asphalt concrete plant if the controlled emissions of sulfur dioxide do not exceed a rate equivalent to the uncontrolled emissions that would result from using fuel oil containing not over 0.7% sulfur.

Although the percentages will vary with the aggregate being used, in Texas we estimate that approximately 50% of the sulfur dioxide emissions will be absorbed by the aggregate mix and/or the scrubbing device or baghouse cake. Ordinarily, therefore, we will consider BACT applied if the sulfur content of the fuel oil does not exceed 1.5% by weight.

It is possible that recycling may present an additional sulfur dioxide problem if the flame or radiaton zone comes in contact with the recycled aggregate. Also, the question concerning SO_2 absorption by the recycled pavement probably will require study. Reevaluation of existing policies may be needed as the recycling plants still will be required to meet the same SO_2 limitations required of plants using virgin aggregate.

To summarize, operators of asphalt concrete plants can expect to be required to meet established air pollution control codes when processing recycled materials. The technology to meet these codes is available but needs to be perfected. Until then, pollution control agencies probably will be reluctant to issue permits for other than experimental recycling projects.