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Pavement recycling is a necessity due to the diminishing supply of available construction materials and increasing regulations concerning the disposal of removed concrete and asphalt pavements. Since the 1950's and 60's recycling has grown to include hot and cold mix asphalt recycling, the use of crushed asphalt pavement as an aggregate base, and the use of Portland Cement concrete as an aggregate base, concrete aggregate, and bituminous aggregate. Crack and seating and rubblizing of concrete pavement are also common forms of recycling in Minnesota.

The Minnesota Local Road Research Board (LRRB) requested that a report be written to provide information regarding the common methods of recycling, and to determine the status of recycling in Minnesota. This report outlines the recycling methods listed above, and gives specifications and mix designs for their use in Minnesota.

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asphalt	break-and-seat
concrete	rubblize
pavement	aggregate
hot-mix	cold-mix

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Recycling of Pavement Materials in the 1990's

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Executive Summary

With the diminishing supply of available construction materials, and increasing regulations concerning the disposal of removed concrete and asphalt pavements, pavement recycling is a necessity. Since the 1950's and 1960's, recycling has grown to include hot and cold mix asphalt recycling, use of crushed asphalt pavement as an aggregate base, and the use of Portland Cement concrete as an aggregate base, concrete aggregate, and bituminous aggregate. Crack and seating and rubblizing of concrete pavement are also common forms of recycling in Minnesota. To provide information regarding the common methods of recycling, and to determine the status of recycling in Minnesota, the Local Road Research Board (LRRB) requested that this report be written.

The report includes information obtained from the following sources:

- literature searches
- interviews
- survey results from Mn/DOT State Aid Office
- survey results from Braun Intertec Pavement, Inc.

The report will focus on the following areas:

- recycling methods
- specifications
- mix design
- methods used in Minnesota

Recycling methods outlined are those commonly used in Minnesota, and specifications and mix designs given are for use in the state.

Materials to be Recycled	Recycling Method	Comments
Asphalt Concrete	Hot-Mix	Most common method use in Minnesota. Salvaged materials combined with new AC or aggregate for new hot-mixture. Allowed as Mn/DOT base, binder, leveling, shoulder, and wear course.
	Cold-Mix	Salvaged material combined with stabilizer for new mix, without heat. Most often used as base under low to medium traffic.
	Use as an Aggregate Base	Used as surface or base course. Must meet gradation for virgin aggregate.
Portland Cement Concrete	Crack and Seat	Concrete left in place and cracked into small pieces. Reduces reflective cracking in AC overlay.
	Rubblizing	Concrete crushed in place, then rolled. Concrete acts as aggregate base. Reduces reflective cracking in AC overlay.
	Remove and Crush	Used as aggregate base, backfill, or bituminous and concrete aggregate. Allowed shoulder surface or base aggregate, and under pavement in some cases.

Introduction

The reuse of pavement material and the associated technology is expanding. Much of the high-profile recycling activities during the 1970's dealt with recycling hot asphaltic concrete. However, the concept of recycling has since turned back to focus on work done in the 1950's and 1960's to include cold-mix recycling of asphaltic concrete and the use of Portland Cement concrete as an aggregate base, concrete aggregate, and bituminous aggregate. Crack and seating and rubblizing of concrete pavement as a form of recycling are also common in Minnesota.

To address the issue of increased material available for recycling and the environmental problems and limitations on dumping these materials into landfills, the Mn/DOT Construction Engineer and the Director of the Office of Materials and Research formed a Salvage Materials Task Force in May of 1990. The purpose of this Task Force was to investigate possible uses of salvaged material and recommend changes in the Mn/DOT specifications to allow the increased use of those materials [1]. Several of those recommendations are given in this report.

Although recycling materials has many benefits, including lower construction costs, conservation of aggregate and asphalt cement, and energy and environmental preservation, there are also some associated problems. These include original pavement materials that may not be suitable for recycling, a shortage of contractors or equipment in the area that are capable of recycling, and long hauls from original pavement site to recycling plant that make pavement recycling uneconomical [2]. Another major problem concerns quality control and mix design procedures. Some procedures exist for mix design and establishing layer coefficients, but they are not widely used or known. All of these factors are considered when determining the appropriate method of recycling and its feasibility for a given project.

Determination of Recycling Method

As stated above, there are many methods of recycling both asphalt and concrete pavements. Life-cycle costs for each alternative should be analyzed. However, an initial survey to determine if recycling is the best rehabilitation technique should first be conducted. Figure 1 shows the alternatives for pavement construction, including recycling. If recycling is selected as an alternative, a specific process must be chosen. In this report, processes used are categorized by the type of paving, material to be recycled, and the end product produced.

Description of Recycling Methods

Asphalt Concrete Pavement

Asphalt concrete pavements can be recycled into pavements through hot and cold-mix recycling methods. A statewide survey of recycling asphalt pavement was conducted by the Mn/DOT State Aid Office during the fall of 1991. Ninety-nine responses from 60 counties and 39 cities were received. This survey did not differentiate among various recycling methods and only addressed the recycling of asphalt pavements. Survey results showed that 860,000 tons of salvaged asphalt pavement material were recycled on 219 projects in 1991. Overall, the survey results indicate that recycling is very much accepted and about 90 percent of all material on a project is either reused, recycled, or stockpiled for future use.

According to the Mn/DOT survey, recycled asphalt is used mainly for surface courses (see Figure 2). Thirty percent is stockpiled for future use, 12 percent is used as base, and 11 percent is disposed of. The use of recycled asphalt is broken down by cities and counties in Figure 3, which shows that counties are much more likely to reuse the material as a surface course. Because cities have much shorter and smaller projects, they are less likely to generate quantities sufficient for a good recycling operation. Thirty-three percent of salvaged city pavements are stockpiled and about 23 percent of the material is discarded.

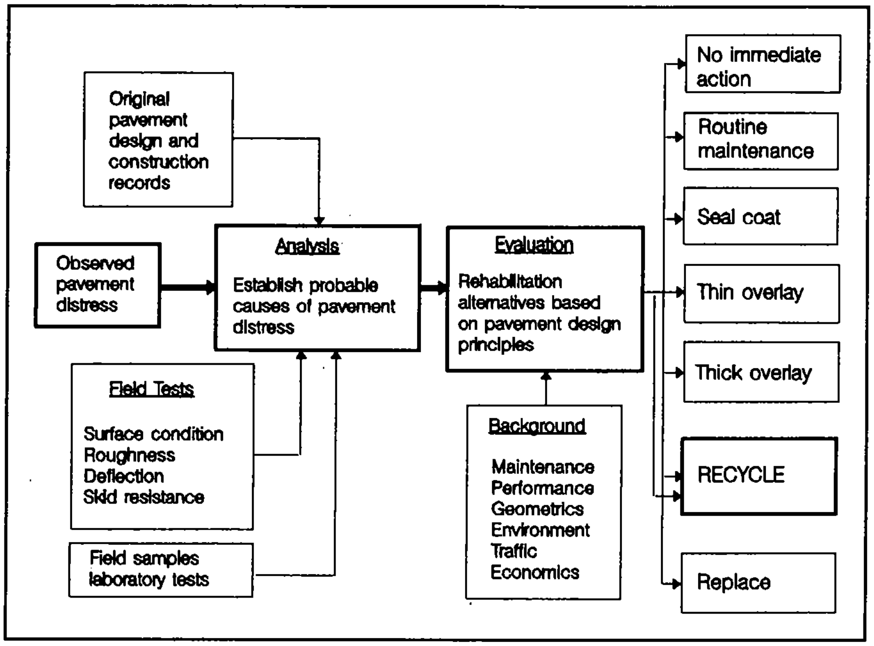

Figure 1. Recycling as a Rehabilitation Method

Another statewide survey addressing the variety of the material recycled, the recycling method, and the use of the recycled material was conducted by Braun Intertec Pavement, Inc. in the summer of 1991 for the Local Road Research Board. The overall survey response rate was 47 percent, of which the county response rate was 50 percent and the city response rate 43 percent. This survey included four kinds of pavement material that could be recycled: hot mixed asphalt, road mixed asphalt, concrete, and aggregate base.

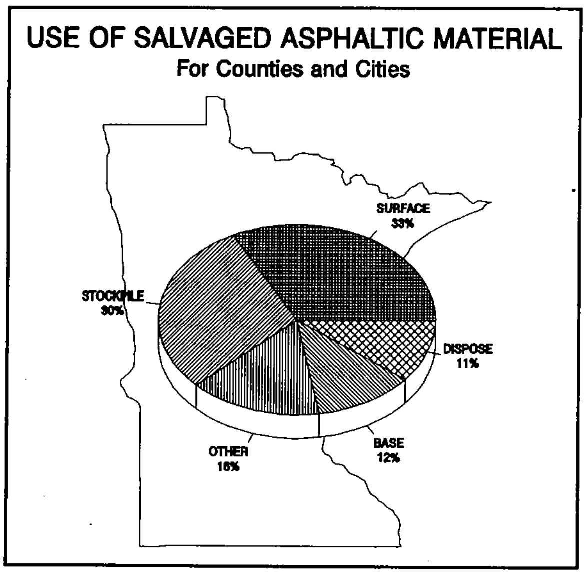

Figure 2. Use of Recycled Asphaltic Material in Minnesota

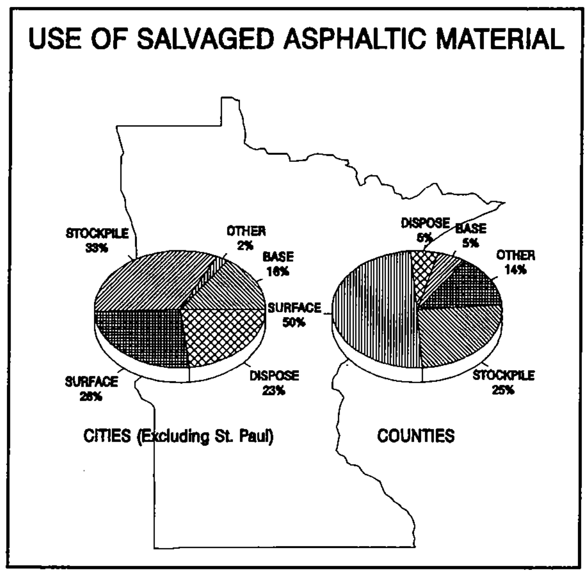

Figure 3. Use of Recycled Material by Counties and Cities

Figure 4 shows the amount of asphalt that is recycled by cold milling and removing and crushing in the state.

That material which is cold milled is most often recycled into hot-mixed surface course. Thirty-one percent is used as base, and 17 percent is placed back into a cold-mixed surface course. Of the material that is removed and crushed, 66 percent is recycled into hot-mixed surface course, 23 percent is used as base, and the remaining 11 percent is recycled into cold-mixed surface. The hot mixed asphalt recycled by pulverizing was used only for aggregate base and is not shown in Figure 4.

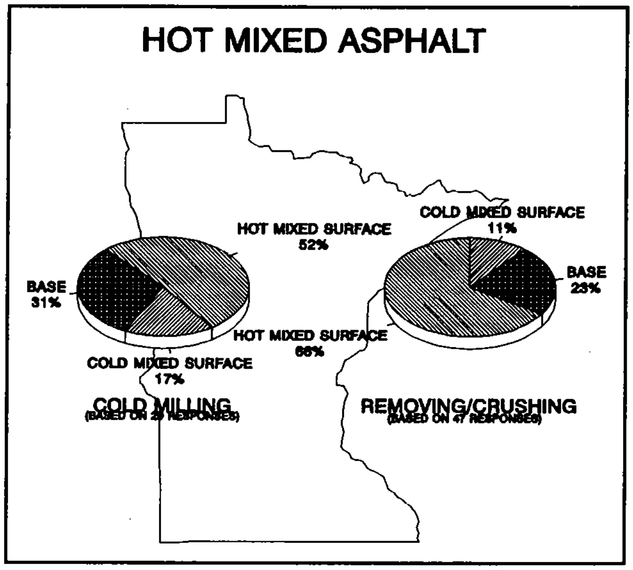

Figure 4. Recycled Hot Mixed Asphalt Use

Hot-Mix Recycling

As shown in Figures 2, 3, and 4, hot-mix recycling has been widely used in Minnesota, and involves combining reclaimed asphalt and/or aggregate materials with new aggregate and asphalt cement in a central plant blending and mixing operation to produce a new hot-mix paving mixture. Hot-mix producers can now make relatively inexpensive additions or modifications to their existing plants and be able to recycle without violating air quality regulations [4].

Hot-mix recycling can make use of existing asphalt pavement that has deteriorated from alligator and shrinkage cracking, reflective cracks, rutting, flushing, corrugations, depression, upheaval, and raveling. It offers several other advantages, including significant structural improvements with little or no increase in thickness required with a virgin mix, and the ability to correct mix deficiencies with the addition of asphaltic cement [5].

Mn/DOT allows the use of hot-mix recycled mixtures as a Type 32 and 42 binder, base, leveling, shoulder, and wear course. Specifications for Recycled Bituminous Mixture Production are given in Section 2331 of the Standard Specifications for Construction [6]. Maximum percentages of various salvaged aggregates allowed are listed in Table 1.

Salvaged Material Types	Maximum Percentage Allowed					
	Type 32 Mixtures			Type 42 Mixtures		
	Non Shoulder			Binder &		
	Base	Level	Wear	Base	Level	Wear
Salvaged Aggregate	100	100	100	100	100	100
Salvaged Asphaltic Pavement	50	50	30	50	30	30
Crushed Concrete	50	0	0	0	0	0
Salvaged Asphaltic Pavement and Crushed Concrete Combination*	85	0	0	0	0	0

* Neither component shall exceed 50 percent of the total aggregate by weight.

Table 1. Allowable Salvaged Aggregate by Mn/DOT [7]

A proper mix design for hot-mixed recycled asphalt includes the following steps [8]:

1. Obtain representative field samples of the reclaimed materials.
2. Perform laboratory analysis to determine:
   - Composition and properties of the reclaimed asphalt materials.
   - Proper amounts of new or recycled aggregate to be added.
   - The type and amount of asphalt modifiers.
   - Mix, compact, and test trial mixtures.
3. Select the optimum combination of mix components that meet the design criteria.

The optimum combination of mix components is obtained when the mix contains enough asphalt cement to ensure a durable pavement. It is also water-resistant, and stable enough to withstand traffic loads without distortion or displacement. The mix must also be workable to permit efficient construction, and contain adequate voids in the compacted mix to provide for slight additional compaction under traffic to avoid flushing, bleeding, and loss of stability [9].

A detailed explanation and method for recycled hot-mix design is given in Chapter 3 of The Asphalt Institute Manual Series No.20 entitled, *Asphalt Hot-Mix Recycling* [10]. The Asphalt Institute and AASHTO overlay design procedures can also be used for designing the thickness of recycled layers as overlays when a portion of the original pavement remains. The physical properties of the recycled mix and materials must be the same as those for virgin mixes and materials used for the same purpose.

Hot-mix recycling is a very economical way of reducing project costs. A 1985 survey conducted by the FHWA found that cost savings through this method of recycling range from 1 to 40 percent when compared to virgin mix, and from 1981-1985, savings for states remained consistently at 25 to 40 percent [11].

Cold-Mix Recycling
Cold-mix recycling has not been widely used in Minnesota. Ramsey county is the most actively involved county in cold-mix recycling, and Sibley, Kandiyohi, Lake, and Winona counties are also actively recycling. Three projects using cold recycling were recently built by Mn/DOT. These are on TH 95 near St. Cloud, TH 71 near Redwood Falls, and TH 30 near Chatfield [12].

The process of cold-mix recycling involves combining, without heat, a processed salvaged material with a stabilizing agent, and sometimes with new aggregate. Cold recycled materials have been used for surface, base, and subbase. The most common use to date has been for base courses under medium to lower traffic conditions. Cold-mix recycling can correct many types of pavement distress involving both surface and base courses. The reuse of aggregate and asphalt from old pavement reduces the new material costs, resulting in overall material savings. Energy conservation, in addition to lower hauling costs may be realized if cold in-place recycling is used.

During cold in-place recycling with bituminous binders, the full flexible pavement structure and portions of the base material or only a portion of the existing asphalt-bounded materials are uniformly crushed and/or pulverized, mixed with a bituminous binder and compacted. There are two types of cold in-place recycling: full-depth (reclamation/stabilization) and partial-depth. The use of full-depth and partial-depth cold in-place recycling dates back to 1910. These two methods are categorized by the depth to which the process is performed. Normal recycling depths for full-depth and partial-depth cold in-place recycling are 4 to 12 in. and 2 to 4 in., respectively.

The bituminous-bound recycled material from full-depth recycling is often used as a stabilized base, whereas that from partial-depth recycling is usually used as a base or surface course on low-to-medium-traffic-volume highways. Other binders, such as lime, portland cement, or calcium chloride, can also be incorporated into the process. Guidelines for selecting a proper binder are contained in "Soil Stabilization in Pavement Structures - A User's Manual," issued by the Federal Highway Administration [13].

For cold-mix recycling, the primary objective of the mix design is to produce a mixture with the same properties as that of a virgin mix. The mix design process for cold-mix recycling is as follows [14]:

1. Obtain representative field samples from the pavement or from stockpiles (ASTM D979).
2. Process samples and extract asphalt for use in mix design (ASTM D2172).
3. Evaluate asphalt content, gradation of aggregate separated from the asphalt and recycled material (ASTM C136).
4. Select amount and gradation of new aggregate.
5. Select asphalt cement or emulsions.
6. Estimate asphalt demand of the combined aggregates.
7. Estimate new asphalt in mix based on original asphalt in the reclaimed asphalt pavement.
8. Mix, compact, and test trial mixture.
9. Establish job mix formula.
10. Adjust job mix formula in field.

Specifications for materials and construction are given below:

Aggregate gradation — A minimum percentage for the nominal maximum size (e.g. 97 percent passing 1 1/2-in sieve with no pieces larger than 4 in.). Mn/DOT requires 100 percent passing 1 1/4-in sieve, 90 to 100 percent passing 1-in sieve. Tests will be performed at a rate of 1 per 5,000 square yard.

A maximum percentage for the amount passing No.200 sieve. The gradation should reflect what is present in the roadway and not what the designer considers to be optimum values. Problems with the existing mix having excess material passing the No.200 sieve may be worsened with this process.

Asphalt binder — A conformation to the appropriate ASTM specifications for the mix emulsion. Mn/DOT specifies CSS-1h.

Sizing and mixing are two major steps in a cold-mix recycling process. For in-place sizing and mixing, four techniques are conventionally used:

- multiple-step sequence (full-depth)
- two-step sequence (full-depth)
- single machine (full and partial-depth)
- single-pass equipment train (full and partial-depth)

Four different kinds of mixing operations can be incorporated into the above techniques. They include blade mixing, transverse-shaft rotary mixing, windrow mixing, or travel-plant mixing. For plant mixing, three types of stationary plants are used: batch, drum, and continuous type plants. Specifications for equipment are based on the four sizing and mixing operations listed above. In the multiple-step sequence method, a motor grader or dozer with front- or rear-mounted ripper teeth should be used for scarifying or ripping the pavement. A sheepsfoot, grid, or similar roller should also be used for initial scarifying and crushing of thin seat-coat roads. A cutter-crusher-compactor attached to the rear of a motor grader with ripper teeth should be used if the scarifying and size-reduction operation is combined. A rotary mixer should be used for removal, crushing, and mixing.

In the two-step sequence method, a cold-milling machine or large pulverizing machine should be used for breaking and pulverizing or sizing. Soil stabilization mixing equipment and travelling mixers should be used for adding stabilizers. In the single machine method, a large cold-milling machine capable of sizing and mixing in a single pass should be used. In the single-pass equipment train method, the equipment train should consist of a cold-milling machine, portable crusher, travel plant mixer, and laydown machine.

Correct construction of the cold in-place recycling includes the following procedures [15]:

1. The drainage conditions must be evaluated as part of the design for the improvement, and the subsurface drainage should then be constructed to improve the roadway drains.

2. The pavement should be broken up to the depth indicated by the thickness design by cold milling, or by scarifying and ripping, followed by size reduction. The machine used should have standard automatic depth and cross-slope controls and be capable of maintaining a constant depth. It should also have screening and crushing capabilities to reduce or remove oversized particles.

3. The emulsified asphalt or hot asphalt cement (binder) should be uniformly mixed with the broken and sized asphalt pavement materials, old granular base and new aggregate, if used. During mixing, the asphalt binder content should be as determined in the job-mix formula amount within a specified tolerance of ± 0.2 percent and maintained at all times. When new aggregate is added to in-place materials, a spreader box or windrow sizer should be used to ensure that the required quantity is evenly placed.

   If cold-mixes are to be prepared by road mixing, accurately sized windrows are essential to ensure the required thickness of pavement and proper proportioning of the asphalt. If water is used to facilitate uniform mixing of the sized material with the asphalt binder, the water and asphalt should be applied separately to the aggregate to provide accurate control.

4. Windrowed mixtures should be spread without segregation and shaped to the desired cross-section by successive passes with a motor grader or with a paver and windrow pick-up machine. Whether the mix needs aeration is decided according to the mix moisture and depth. Usually, if the water content of the mix is bellow 2 to 3 percent and the lift thickness is less than 3 in., aeration is not needed. Mixtures that do not require aeration may be spread to the required thickness immediately after mixing. Those that require aeration should be deposited upon the roadbed in a windrow. Because of evaporation, the lift thickness should be limited to the thickness resulting in compacted thicknesses less than 3 inch for dense-graded mixes and less than 4 inch for open-graded mixes. When multiple lifts are required, curing time should be allowed between successive lifts.

5. A control strip for the rolling pattern should be constructed at the beginning of work. It should have an area of at least 400 square yards, and be of the same thickness as the lift. To control density, sample locations should be established in the control strip on a random basis and the density at each point measured. The breakdown rolling should begin immediately before or at the time the emulsion starts to break. To eliminate wheel tracks by a motor grader, the roller should follow directly behind the motor grader. If the mixture exhibits undue rutting or shoving, rolling should be stopped and compaction not attempted until there is a reduction in moisture content. For a smooth riding surface, the motor grader should be used to trim and level as the rollers complete compaction of the lift.
   Use of a 25-ton pneumatic roller is suggested for lifts greater than 3 inches thick.

6. A surface treatment is required to provide waterproofing. Surfacing materials (chip seal or dense hot mixes) should be placed on the recycled base. Moisture content should be reduced to 1.5 percent before placement of the surface (summer curing of seven to fourteen days). It is suggested that this be done in the heat of the summer.

Because statistically based quality assurance specifications have not been developed, guidelines for quality control are taken from experienced agencies and are listed as follows [16]:

- Cold in-place mixtures should not be placed in depths greater than 3 to 4 in. to provide for adequate curing, and depths not be less than about 2 in. to minimize segregation.
- The compacted mixtures can be rerolled to obtain additional density within the first two to three days when softening of the mixtures may occur.
- Excessive initial compaction should be avoided.
- Traffic should not be allowed to compact the recycled pavement for a minimum of two hours after the initial compaction.
- If the surface starts to ravel under traffic, traffic should be controlled and a finishing roller should continue to compact the pavement before sealing.
- Recycling operations should not be performed when the weather is foggy or rainy, or when the air temperature is below 50F.

Material savings and heat energy conservation offered by cold-mix recycling cut initial costs considerably. Other benefits include:

- Significant structural improvement of deteriorated pavement,without changes in geometry and shoulder reconstruction
- Elimination of some reflective cracking with adequate depth of pulverization and reprocessing
- Improvement of ride quality
- Minimization of hauling costs
- Improvement of profile, crown, and cross slope
- High production rate
- Minimization of air quality problems resulting from dust, fumes, and smoke
- Improvement of frost susceptibility

There are also several major disadvantages of cold-mix recycling, including:

- Quality control problems
- Required curing for strength gain
- Strength gain and construction susceptibility to climate
- Construction variation with cold in-place full-depth recycling
- No nationally recognized mix design procedures

Use as Aggregate Base

Asphalt pavement can also be crushed and used as an aggregate base or surface material. The Salvage Materials Task Force appointed in May of 1990 recommended that Mn/DOT Specification 3138 be revised to increase the allowable bituminous content in base and backfill material from 2 to 3 percent. This limitation does not apply to surface or shoulder use where 100 percent recycled material may be used. The material must meet the gradation specified for virgin aggregate.

The City of Minneapolis routinely uses salvaged bituminous mixture as surface course for haul roads and alleys. The material is ground to 3/4-inch minus size, spread, and compacted. Winona County uses 100 percent milled recycled asphalt pavement for shouldering. They use their own forces and equipment, and limit their work to hot summer days. Pneumatic rollers are used, and the millings are slowly rolled all day. Rick Arnebeck, County Engineer, claims good results with this process [17].

Concrete Pavement

Portland Cement concrete pavements can be recycled using several methods. By crack and seating or rubblizing, the pavement can be used as a base for an asphalt overlay, a form of in-place recycling. The pavement can also be removed and crushed for use as bituminous or concrete aggregate, base course, or backfill. According to the LRRB survey mentioned earlier, only 12 percent of Minnesota agencies have experience with crack and seating, as shown by Figure 5. Eighty percent of the concrete that is recycled is used as bituminous aggregate, and the remaining 20 percent is used as aggregate base (see Figure 6). Note that no survey respondents use recycled concrete for concrete aggregate.

Crack and Seat

With this method of recycling, the concrete pavement is left in place and cracked into small pieces, rolled to seat the pieces into the underlying base, and overlaid with asphalt mix. The procedure may reduce the amount of reflective cracking in the overlaying pavement by limiting joint movement and reducing stresses in the asphalt overlay [18]. The term "crack and seat" is used to describe the process of breaking non-reinforced concrete pavement. "Break and seat" is used to describe the process on reinforced pavement.

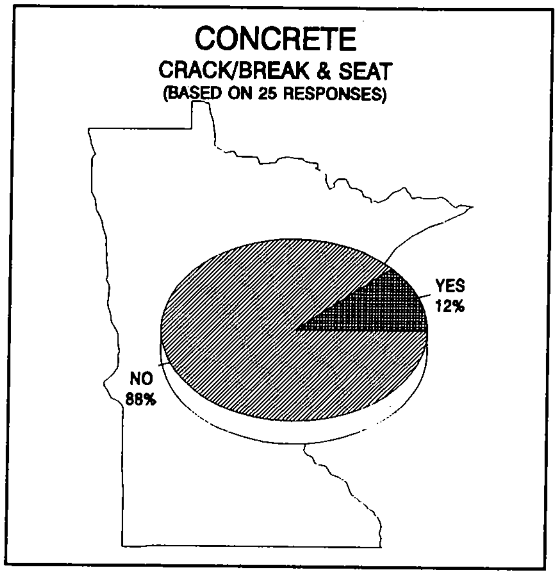

Figure 5. Use of Crack & Seat

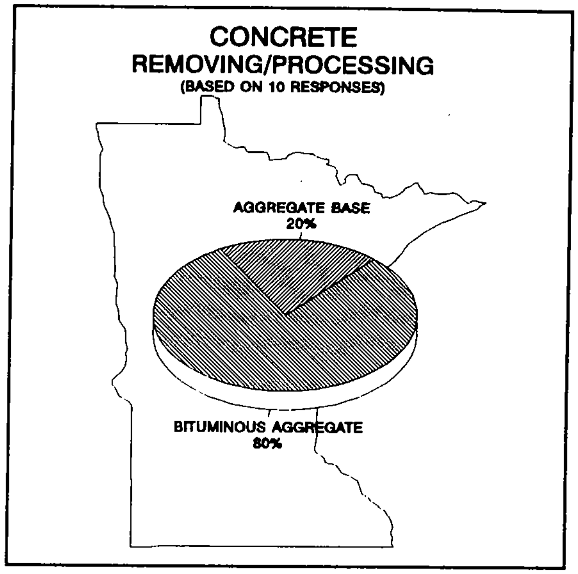

Figure 6. Use of Concrete Recycled by Removing/Processing

The cracking can be completed with one of many machines available. Use of the guillotine hammer is favored by Mn/DOT, and consists of a hammer that is dropped from a height varying from about 18 to 24 inches. The distance between impacts is controlled by the operator as well as the speed at which the machine moves along the pavement.

Prior to cracking, existing joints and cracks in the pavement should be inspected, and deflection testing performed to determine if problems exist below the concrete. Joint sealant should be removed, along with existing asphalt overlays. Culverts and pipes should be marked and avoided with the hammer [19]. The optimum size of cracked pieces is yet to be established, but for pavements on reasonably firm base or subbase, 2 to 3-foot pieces with a 3 to 5 inch overlay have performed best to date [20]. Mn/DOT requires transverse cracking at an interval of 3 feet, and no cracks are allowed within 2.5 feet of an existing joint or crack.

If a pavement is to be cracked and seated, care should be taken to not rubblize it during cracking. Destructive techniques, such as the use of a headache ball and chisel nose pile drivers, as well as excessive energy lead to undesirable spalling and loss of structural strength. Correct cracking methods result in fine cracks, extending full-depth through the pavement. Care should also be taken when working near joints and edges to avoid spalling and longitudinal cracking [21].

To ensure quality control on a crack and seat project, the crack pattern and spacing should be inspected often to ensure that the pavement is not being shattered. Crack fanning, in which the cracks run vertical from the surface zone but develop lateral tendencies about halfway down the slab, is also undesirable. The pavement can be cored at the cracks to determine if they are running full-depth. Also, water can be used to detect the fine crack pattern and to verify that cracking has occurred [22].

Once the pavement has been cracked to the level specified, it is to be rolled to seat it firmly into the base. In general, seating is most effective when done with a heavy pneumatic roller. Two passes with a 50-ton pneumatic have given good results, as has rolling with a fully-ballasted 35-ton pneumatic roller. Steel drum and vibratory rollers tend to bridge over cracked pieces, not seating them properly. Since Mn/DOT allows traffic to ride on cracked and seated pavement, traffic delays can be kept to a minimum.

To determine the thickness of the asphalt overlay, the National Asphalt Pavers Association (NAPA) suggests that every 1 inch of in-place seated concrete is equal in strength to 1-1/2 inch of bituminous. Age and condition of the concrete pavement will influence the structural layer coefficient selected for use in the design procedure given in the 1986 AASHTO Guide for Design of Pavement Structures.

Rubblizing
Rubblizing involves the in-place crushing of concrete pavement to pieces 1 to 6 inches in size, effectively reducing the slab to a crushed aggregate base. This is a relatively new technique and has not been widely used in Minnesota.

Prior to crushing, any existing asphalt overlay should be removed. Once rubblized, any exposed rebar should be cut off and removed, and the crushed pavement compacted with at least two passes of a vibratory roller weighing at least 10 tons. Unlike cracked and seated pavement, traffic should not be allowed to travel over the crushed concrete.

To determine the thickness of the asphalt overlay, the AASHTO Guide for Design of Pavement Structures can be used, assuming a granular equivalent of 1.25 in the Mn/DOT design procedure [23].

State Highway 3 south of 494 was recently overlaid after the existing concrete pavement was rubblized. The existing asphalt overlay was milled and recycled, and the underlying concrete was cracked into pieces ranging in size from 9 inches at the bottom of the slab and 1 inch at the top. A high frequency, low amplitude vibration pavement breaker was specified.

Dan Wegman, the Mn/DOT Project Engineer, concluded that, aside from the cracking operation proceeding too slowly for paving to follow within the specified five-day cover up period, the project went well. The pavement structure did not suffer, and increased permeability of the cracked concrete may offer an additional benefit. Recommendations from the project include: specifying a back-up breaker on site to avoid delays, specifying a cover-up time for the cracked pavement, providing for dust control, and specifying nightly inspections of shattered concrete to remove any rebar that becomes exposed under traffic [24].

Remove and Crush
A third method of recycling concrete pavements involves removal of the pavement and crushing it for use as an aggregate base, backfill, or aggregate for bituminous or concrete mixtures. For all uses the procedure is as follows: all joint sealant and asphalt patches are removed, the concrete is broken and rebar is removed, the concrete is crushed and any additional exposed rebar is removed, the concrete is crushed again, and then stockpiled. Rebar must be removed by hand, which is very labor-intensive.

The Salvage Materials Task Force recommended that Mn/DOT Specification 3138 be revised to allow the use of crushed concrete as a surface or base course in the following instances [25]:

1. As aggregate to be blended with other permitted aggregate materials, provided that all of the crushed concrete aggregate shall be retained on the No. 4 sieve, and the quantity does not exceed 15 percent by weight of the total composite aggregate mixture.

2. As base aggregate placed on a *granular subgrade* provided the base thickness does not exceed three inches.

3. As a surface or base aggregate in shoulder areas, even in locations where perforated, drains are in place (including structure drains).

4. As base aggregate under the pavement where the only subsurface drains are behind retaining walls or other structures.

The Task Force also recommended that the Mn/DOT Specification 3149 for Granular Material be revised to allow the use of crushed concrete as a granular material, provided that:

1. All concrete material shall be larger than the No. 4 sieve.

2. Concrete material between the No. 4 sieve and 2 inches shall not exceed 15 percent by weight, based on the composite of all material smaller than 2 inches.

3. Concrete material larger than 2 inches is not restricted. Such material must be blended/mixed, as appropriate, with other non-concrete materials to meet all gradation and construction requirements, e.g. Mn/DOT 2105.

4. For perforated drains associated with retaining walls/structures, the above provisions 1 through 3 shall apply only to that portion of the select granular modified (0 to 10 percent minus 200), above the invert of the perforated pipe and within a zone 18 inches from pipe centerline and up and away from the structure at a 1/2:1 slope.

Crushed concrete may also be used *below* the invert elevation of any perforated subsurface drain pipe, and as a stabilizing aggregate [26].

The City of Minneapolis routinely uses crushed concrete as a base for city streets. Their gradation specification is similar to Mn/DOT Class 5 aggregate, with a slight variation in the percent passing the No. 10 and No. 40 sieves [27]. The gradations of both are given in Table 2.

Sieve	Percent Passing	
	Mn/DOT Class 5	City of Minneapolis
1"	100	100
3/4"	90-100	90-100
3/8"	50-90	50-90
#4	35-80	35-80
#10	20-100	20-65
#40	5-35	10-35
#200	3-10	3-10

Table 2. Crushed Concrete Gradation

Martin County routinely uses recycled concrete as aggregate for bituminous mixtures. The County crushes their old concrete to 1-1/2 or 2 inch maximum pieces, which are split on a 3/8-inch screen and separated into two stockpiles. No gradation is specified and the blend of recycled and virgin aggregate is varied after a trial mix is completed. The County will often charge contractors for the aggregate and reports this figure to the State Aid Office to offset the cost of new construction [28].

As an aggregate for new concrete pavement, crushed concrete works very well. When used as a coarse aggregate, there is no effect on the mix strength, durability, or workability. When used as a fine aggregate, the mix is less workable and needs more water [29]. Most agencies, in addition to Mn/DOT will not allow the use of the recycled fines. Mn/DOT has developed specifications for three recycled mixes: 3A40R, 3A30R, and 3A20R. The mix design must be approved by the engineers in writing and the source of the recycled concrete must be determined satisfactory for the use intended.

To recycle the concrete, it is first crushed into pieces less than 1-1/2 inch in size. The crushed material is then separated over a 3/8-inch screen and the two products piled separately to minimize segregation. The stockpiling should be in accordance with standard specifications, and excessive fines must be controlled so that no more than 5 percent pass a No. 200 sieve. Excess fines may be used for other purposes. Washing of the material is not necessary, but all rebar should be removed. The crushed pieces can then be used in the same manner as virgin aggregate [30].

Status of Recycling in Minnesota

Overall, both the Mn/DOT and LRRB surveys found that about half of all Minnesota cities and counties have experience with recycling. Counties are much more likely to recycle than cities (see Figure 7). As explained earlier, this is partly due to the fact that city projects are usually smaller and are less likely to produce large quantities of salvaged material. An increasing amount of agencies are requiring that salvaged materials be recycled or that recycled materials be used in construction, as illustrated by Figure 8.

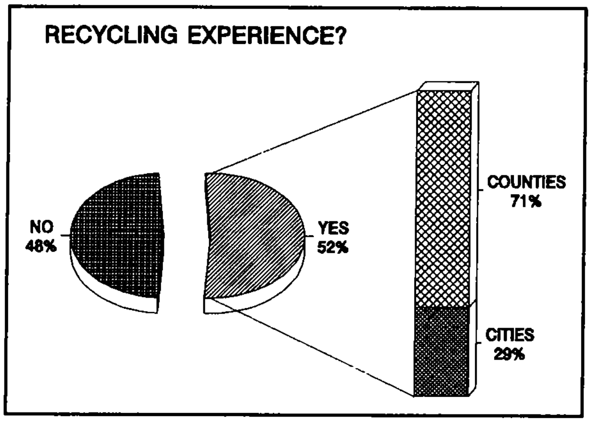

Figure 7. Recycling Experience of Minnesota Local Agencies

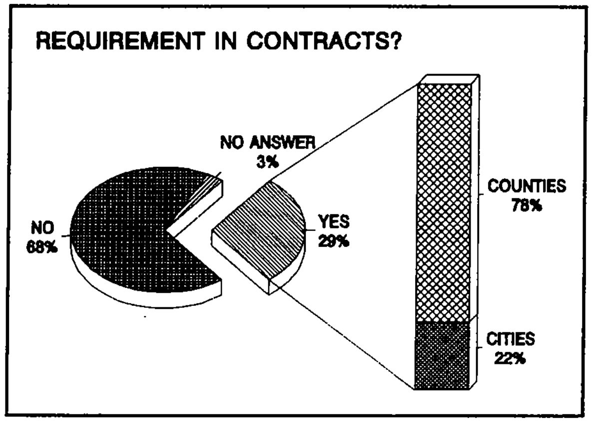

Figure 8. Require Recycling in Contracts

There are still several problems related to recycling which discourage agencies from having an active recycling program. The problems that Minnesota agencies cite are given in Figure 9, and include mix variability, poor mix quality, and stockpile management. Barriers to those agencies getting involved in recycling include small scale projects, mix quality control, stockpile management, and local attitudes. All barriers that were cited in the survey are shown in Figure 10.

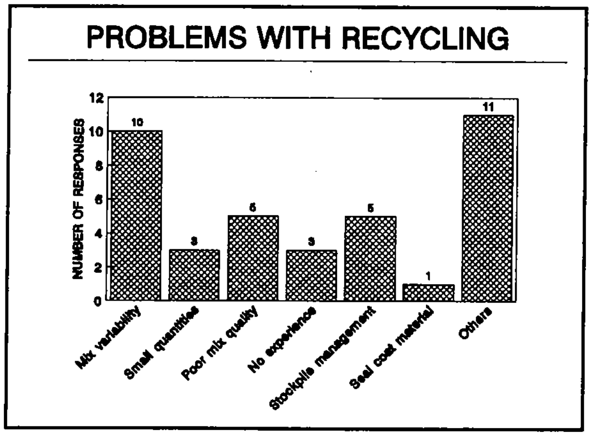

Figure 9. Problems with Recycling

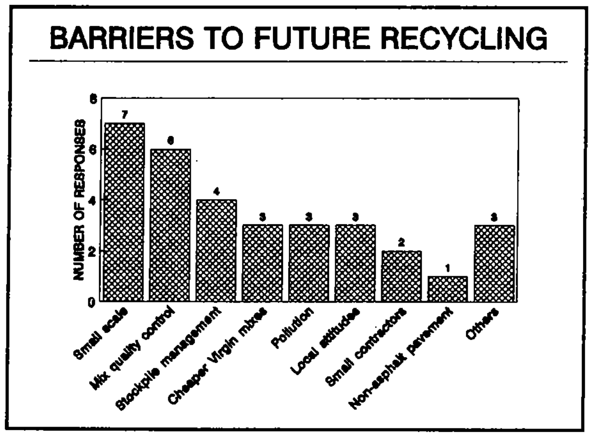

Figure 10. Barriers to Further Recycling

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