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Minnesota Heat-Transfer Method for Recycling Bituminous Pavement

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A method for hot-mix-recycling of in-place bituminous pavement that was developed for use on a roadway project in Maplewood, Minnesota, is described. An urban four-lane street was reconstructed to a four-lane divided roadway with turn lanes and transit bus turnouts. The bituminous material was salvaged and recycled along with the upper 0.33 m (1 ft) of gravel base. The old material was scarified, picked up, and hauled to the mixing plant where it was run through a normal three-crusher plant (one jaw and two rolls) and stockpiled. The upper 0.33 m of gravel base was loaded off the roadway, hauled to the plant site, and stockpiled. The salvaged gravel was conveyed from the stockpile to the dryer where it was heated to 232°C to 260°C (450°F to 500°F). The unheated, crushed, salvaged bituminous material was conveyed directly from the stockpile to the weigh hopper above the pug-mill mixer. For the base course, 50 percent salvaged bituminous material was blended with 50 percent salvaged gravel at the mixer for 20 s; then 3 percent asphalt was added and wet-mixed for 30 s. The proportions for the binder course were 40 percent salvaged bituminous, 60 percent salvaged gravel, and 3.5 percent asphalt. The paving was done by use of conventional equipment and conventional methods. Test results for the finished product and the performance of the pavement to date (winter, spring, and summer) indicate that the structure is comparable to a conventional full-depth asphalt base.

Recent developments in the road-building industry have prompted a reassessment of the recycling of bituminous pavements and base aggregates on construction projects. These developments were the rising cost of asphalt, an awareness of the need to conserve finite deposits of nonrenewable natural resources, and a difficulty in finding environmentally and politically acceptable disposal sites for the debris that results from construction and demolition.

Recycling of in-place road materials is not a new concept. In the past, however, when pavement surface and base materials were reused in selected subgrade or base applications, no benefit was realized from the old asphalt binder. Whether the reused material was a gravel base or a pavement surface material, the assigned structural value was no more than that of gravel. A more cost-effective alternative would be to rejuvenate the old asphaltic binder of the in-place bituminous material. Recycling and placing this material as a hot mix rather than an aggregate base would produce a higher strength pavement structure.

The opportunity to hot-mix-recycle came when Raymond Hite, then superintendent of public works in Maplewood, Minnesota, came to the Minnesota Department of Transportation (DOT) for assistance with a project he felt should include the recycling of the in-place bituminous pavement. This project was an urban street of conventional flexible pavement design that was to be reconstructed as a full-depth asphalt pavement. Shortly thereafter, the Minnesota Local Road Research Board authorized funds for setting up and evaluating an urban and a rural bituminous recycling project.

In reviewing the experience of other agencies, which used direct heat in the softening and mixing process, it was noted that the major problem was air pollution in the form of smoke—a problem caused, for the most part, by the burning of asphaltic cement. In at least one other case, a patented process had solved the air pollution (smoke) problem. That process called for a new, completely redesigned drum mixer that used an indirect method of heating the salvaged bituminous mix. A proprietary softening agent was also added to the salvaged bituminous material during mixing operations. The use of that process would have meant buying or leasing the indirect-heating drum mixer and the payment of royalties. It was determined that this would not be cost-effective for the Maplewood project, which called for only 18 144 Mg (20 000 tons) of recycled mix. Coupled with these problems of pollution and expense was the fact that the recycling done thus far was limited to quite low production rates at the mixing plants.

Thus, it was concluded that on this project, because of the small amount of bituminous material that was to be produced, the only cost-effective method would be to use conventional equipment with minimal modifications; this led to the development of the Minnesota heat-transfer method.

This report describes the Minnesota heat-transfer method and the design and construction of this project, which used salvaged bituminous pavement and salvaged aggregate for the full-depth bituminous pavement. This project was located in Maplewood, adjacent to and partially within the headquarters complex of the Minnesota Mining and Manufacturing (3M) Company. The project was a joint effort of the city of Maplewood, the Minnesota DOT, C.S. McCrossan, Inc., and the Minnesota Local Road Research Board.

HEAT-TRANSFER CONCEPT

The problem on the Maplewood project was how to recycle the in-place roadway materials into a usable recycled bituminous mixture cost-effectively and yet without excessive smoke pollution. The materials available for recycling were approximately 4536 Mg (5000 tons) of old bituminous material and 13 608 Mg (15 000 tons) of gravel base. The project required approximately 18 144 Mg (20 000 tons) of recycled bituminous mixture. It became evident that cost-effectiveness required using conventional equipment with minimal modification.

Initially, it was proposed that the salvaged bituminous material and aggregate be blended before they were introduced into the dryer of the mixing plant. But a review of past experience with this method indicated that this could not be done without smoke pollution and reduced plant production. At one of several meetings, the idea of heat transfer was conceived. Instead of blending the salvaged bituminous material and aggregate before introducing them into the dryer, it was proposed to "super heat" the salvaged aggregate in the dryer and combine it with the salvaged bituminous material away from the intense heat of the dryer.

A laboratory experiment was set up to test the concept. In the experiment, the clean aggregate was heated to 193° C (380° F) and then combined and mixed with salvaged bituminous material that was at room temperature. The results of the heat transfer showed that the different proportions of salvaged bituminous material and salvaged aggregate would combine readily within 2 to 3 min. The temperature of the combined mix was almost the theoretical straight-line relation between the room temperature of the salvaged bituminous material and the hot salvaged aggregate.

The concept was discussed with several contractors. Some felt that the concept could be adapted easily to conventional mixing plants at a minimal cost. A few were sure that the plant would get plugged up when the materials were combined and thus significantly reduce mixture production.

The only remaining problem was determining the mixing time and the temperature of the recycled mixture during the initial stages of production. Otherwise, plant operation was excellent, production was normal, and there was no smoke.

DESCRIPTION OF THE PROJECT

The existing roadway was a 14.6-m (48-ft) wide, four-lane bituminous roadway adjacent to the 3M Company headquarters complex east of St. Paul. It was constructed in a series of projects from 1959 to 1964. The structure was nominally 10.2 cm (4 in) of bituminous material and 30.5 cm (12 in) of gravel base over a sandy loam subsoil (A-3) with an R-value of 75 (Hveem stabilometer). It had served traffic well, but increased traffic volume and higher axle loads indicated the need for structural and geometrical upgrading. The roadway was to be upgraded to a four-lane expressway with channelization, concrete curb and gutter, and bus turnouts. The new structural design was 18 cm (7 in) of bituminous base, 3.8 cm (1.5 in) of bituminous binder (leveling), and 1.9 cm (0.75 in) of taconite-tailings wearing course (a good, hard rock waste product with good frictional properties).

PRELIMINARY LABORATORY TESTS

Before the mix was designed and special contract provisions were written, five samples were taken of the bituminous material, gravel base, and subgrade to a depth of 1.2 m (4 ft). These samples were submitted to laboratory analysis and testing. The samples of bituminous material were softened and remolded.

The tests run were (a) density and stability values by the Marshall method, (b) percentage voids by the Rice method, and (c) percentage asphalt by AASHTO T 164-74, method C. The recovered asphalt was tested for (a) penetration (AASHTO T 49) and (b) ductility (AASHTO T 51). These results are given in Table 1.

Sieve analysis was run on the aggregate after asphalt extraction (AASHTO T 30-74). Results of these tests are given in Table 2. The five samples of gravel base were also tested by sieve analysis (AASHTO T 27-74). The tabulated gradation results are given in Table 3.

The test results showed that all materials available for recycling were comparable to virgin material with the exception of the percentage of material passing the 0.075-mm (no. 200) sieve that would be specified for a conventional mix. Therefore, it was felt that the salvaged bituminous material and the salvaged gravel would provide an adequate recycled bituminous mixture. The special contract provisions that pertained to the recycling operation were then drawn up.

SPECIAL PROVISIONS OF CONTRACT

The following is a condensed, slightly edited version of the special contract provisions for the project.

S-1302: Award of Contract

As a condition precedent to award of this contract, the successful bidder shall provide a plan for eliminating possible air pollution. This plan shall meet with the letting authority's approval before award of the contract and be in accordance with the rules, regulations, and standards adopted and established by the Minnesota Pollution Control Agency and in accordance with the provisions of Minnesota Highway Department (MHD) 1717.

S-2105: Excavation and Embankment

Excavation and embankment construction shall be performed in accordance with the provisions of MHD 2105 except as modified below.

Table 1. Samples of existing bituminous material before construction.

Test	Sample 1	2	3	4	5
Bituminous mix					
Density,[a] kg/m³	236.6	229.9	241.4	227.6	228.6
Stability,[a] N	5536	7454	10 382	7160	6626
Voids,[a] percent	7.0	9.8	5.4	12.2	9.5
Asphalt,[b] percent	3.8	3.6	3.9	3.1	4.0
Recovered asphalt					
Penetration[c]	80	31	127	29	40
Ductility,[d] cm	150+	126	150+	93	150+

Note: 1 kg/m³ = 0.062 lb/ft³; 1 N = 0.2248 lbf.

[a]Test procedures on file at Materials Office, Minnesota DOT.
[b]AASHTO T 164-74, method C.
[c]AASHTO T 49.
[d]AASHTO T 51.

Table 2. Sieve analysis of aggregate after extraction of existing material (AASHTO T 30-74).

Sieve Size[a] (mm)	Percentage Passing Sample 1	2	3	4	5	Average	BA-2 Specification[b]
19	100	100	100	100	100	100	100
16	99	99	99	100	98	99	95-100
9.5	89	83	81	87	88	86	65-95
4.75	74	71	69	74	76	73	
2.0	62	59	59	60	64	61	35-65
0.425	28	26	34	29	32	30	10-35
0.075	7.7	6.3	10.7	6.4	6.9	7.6	1-7

[a]Corresponding U.S. sieve sizes: 0.75, 0.625, and 0.375 in and nos. 4, 10, 40, and 200.
[b]Current Minnesota DOT gradation specification for aggregate used in bituminous mixtures.

Table 3. Sieve analysis of in-place gravel.

Sieve Size[a] (mm)	Sample 1	2	3	4	5	Average	C1-5 Specification[b]
25	100	100			100	100	100
19	98	99	100	100	99	99	90-100
16	94	97	99	96	98	97	
9.5	81	85	85	80	85	83	50-90
4.75	69	72	69	68	69	69	35-80
2.0	61	63	55	60	56	59	20-65
0.425	33	34	29	35	29	32	10-35
0.075	8.0	7.6	8.2	8.9	7.4	8.0	3-10

[a]Corresponding U.S. sieve sizes: 1, 0.75, and 0.625 in and nos. 4, 10, 40, and 200.
[b]Current Minnesota DOT gradation specification for aggregate used in base construction (AASHTO T 27-74).

Salvaged Aggregate

Salvaged aggregate shall include the existing sand, gravel, or crushed rock materials that lie between the bottom of the existing bituminous surface and a plane parallel to and 30.5 cm (12 in) below the bottom of the existing bituminous surface that can be salvaged and used without pulverization. The gradation of the salvaged aggregate material shall be reasonably uniform from fine to coarse with 100 percent passing the 37.5-mm (1.5-in) sieve.

Salvaged Bituminous Mixture

Salvaged bituminous mixture shall include the bituminous mixture in the existing bituminous courses. As a part of the salvaging operations, the bituminous mixture shall be processed or pulverized so as to provide a reasonably uniform gradation from fine to coarse with 100 percent of the material passing the 37.5-mm (1.5-in) sieve.

Salvage Materials

Salvage materials will be measured by the ton. Salvaging material from the existing roadway, processing the material as specified, and placing the processed material in stockpiles shall be one operation constituting a complete unit of measure; removing material from stockpiles and placing it in the work as specified shall be a separate operation constituting another complete unit of measure. The salvaged aggregate and the salvaged bituminous mixture after processing shall be placed in two separate, distinct stockpiles. If necessary, to facilitate crushing and processing, up to 20 percent salvaged aggregate may be incorporated into the salvaged bituminous mixture.

S-2331: Plant-Mixed Bituminous Pavement

A plant-mixed bituminous pavement shall be constructed in accordance with the provisions of MHD 2331 and as shown in the plans, except as modified below or supplemented by using asphalt cement (AC) with the appropriate penetration for producing the specified mixtures:

Mixture	AC Penetration
Binder course	85/100 or 120/150
All base courses	120/150

S-2331.3: Construction Requirements

Under 2331.3B, add the following:

The contractor shall submit, prior to the award of the contract, an acceptable proposal for preventing or eliminating excessive air pollutants.

Under 2331.3C1a(2), Feeder for the Drier, add the following:

A means shall be provided for adding the salvaged bituminous mixture, when required, to the heated aggregate after the aggregate has left the drier. This means shall provide for positive control on proportioning the salvaged bituminous material into the mixture.

Under 2331.3C1a(3), Drier, add the following:

When it is required to add the salvaged bituminous mixture for the bituminous base and binder courses mixtures, it may not be necessary to run the salvaged bituminous mixture through a drier.

Under 2331.3E, the provisions of MHD 2331.3E(1) are supplemented as follows: The approximate mixture proportions of salvaged bituminous mixture and salvaged aggregate to be used in the bituminous base and binder courses shall be as given below. These courses shall be placed in the areas shown in the plans.

Mix	Approximate Mixture Proportions: Salvaged Bituminous	Salvaged Aggregate
Base	20-40	60-80
Binder	20-40	60-80

In addition, a control section shall be constructed where shown in the plans.

Under 2331.3F1, delete the first three sentences of the third paragraph and use the following in lieu thereof:

The aggregate shall be heated to a temperature as designated by the Engineer. This temperature may be in excess of 107°C (225°F). When the aggregate reaches the mixer, either by itself or in combination with the salvaged bituminous mixture, it will be at a temperature which will not cause damage to the asphalt being added.

All costs of equipment modification for the bituminous mixture composed partially of the salvaged bituminous mixture, including the adoption of any of the alternatives included in the bidder's contingency plan for elimination of air pollution, shall be paid for as a lump sum not to exceed $15 000. The contractor shall submit to the engineer before final payment an itemized list of costs incurred for this equipment modification.

Payment at the contract price per ton of mixture for each of the types of mixture shall include all costs of preparation, mixing, and placing the respective mixtures.

REMOVAL AND PROCESSING OF OLD BITUMINOUS MATERIAL AND AGGREGATE BASE

The contractor tried several methods for scarifying and reducing the size of chunks before hauling the old bituminous material 50 km (31 miles) to the plant site at Osseo, Minnesota. The contractor concluded that the most effective method for this project was to scarify and windrow the old bituminous material with a motor grader and process it through a conventional crushing operation at the plant site in Osseo (Figures 1 through 4).

The salvaged bituminous material was hauled to stockpiles, either temporarily at the job site by a self-loading scraper or to the plant site by trucks. The contractor was allowed to pick up a portion of the aggregate base with the salvaged bituminous material to facilitate removal and crushing operations.

The salvaged bituminous material was crushed to pass the 37.5-mm (1.5-in) sieve at the contractor's conventional crushing plant without any unusual difficulties. The crushers were able to handle the size of chunks (Figure 3) as they came from the job without any intermediate steps. No problems were encountered in the crushing operation even at an ambient air temperature as high as 38°C (100° F). The crushing operation provided a uniform, well-graded material.

The remainder of the upper 30.5 cm (1 ft) of aggregate base was windrowed and hauled to separate stockpiles in the same manner as the salvaged bituminous material (no crushing was required).

Figure 1. Motor grader ripping up old bituminous pavement for recycling.

Figure 2. Overall view of section of ripped-up pavement.

Figure 3. Closeup view of ripped-up chunks of pavement.

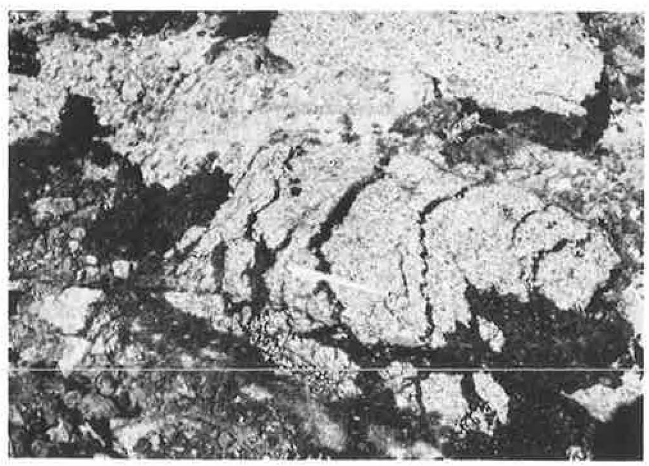

Figure 4. Overall view of crushing plant.

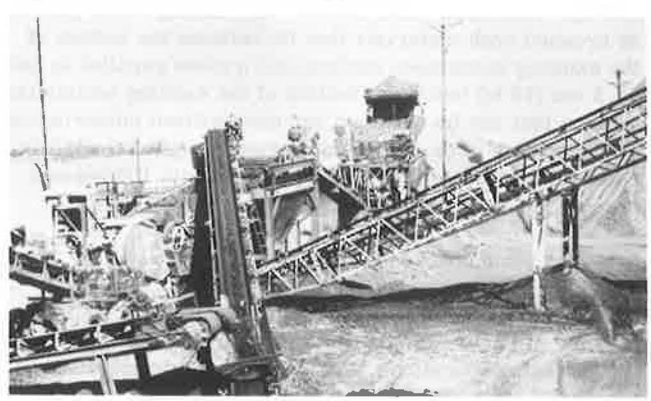

Table 4. Laboratory results for trial mix.

Property	Mix 1	2	3	4	5	6	7	8
Proportion bituminous to aggregate	20/80	30/70	40/60	50/50	20/80	30/70	40/60	50/50
Density, kg/m³	216.8	218.8	223.0	221.1	224.8	225.9	228.5	226.8
Stability, N	2755	3849	3827	4330	3889	4779	4730	4704
Voids, percent	Test not completed because of stripping				10.7	11.4	8.5	9.7
Cold water abrasion loss,[a] percent	Test briquets crumbled, failure				27.5	24.6	21.2	21.8

Notes: 1 kg/m³ = 0.062 lb/ft³; 1 N = 0.2248 lbf.
For mixes 1 through 4, 2 percent asphalt added by weight (AC-1, penetration 120/150); for mixes 5 through 8, 4 percent asphalt added by weight (AC-1, penetration 120/150).

[a]Minnesota test procedure for indication of stripping; less than 12 percent loss desired.

RECYCLED BITUMINOUS MIX DESIGN

After a sufficient amount of crushed, salvaged bituminous material and salvaged gravel had been stockpiled (August 1976), samples were submitted to the Minnesota DOT materials laboratory for mix design.

The Marshall mix design method of testing (AASHTO D 1559) was used on eight mixes as follows (percentage by weight):

Mix	Salvaged Bituminous (%)	Gravel (%)	AC-1 Percentage	AC-1 Penetration
1	20	80	2	120/150
2	30	70	2	120/150
3	40	60	2	120/150
4	50	50	2	120/150

Mixes 5 through 8 used the same proportions of salvaged bituminous and gravel as mixes 1 through 4, but 4 percent AC was added instead of 2 percent. The results of these mixtures are given in Table 4.

As a result of these tests, it was recommended that 3 percent AC-1 (penetration 120/150) be added for bituminous base design and 3.5 percent for bituminous binder, based on Marshall design criteria, and that mix proportions use 40 to 50 percent of the salvaged bituminous material.

As a further check, a set of trial mixes was done with 3.5 percent added AC and 40 and 50 percent salvaged bituminous materials. In a second identical set, the salvaged bituminous was heated slightly to 66° C (150° F) in response to the contractor's suggestion on plant modification. Another mixture was mixed in a routine manner by using 100 percent salvaged gravel and 4.5 percent AC. The test results for these mixes, given below, indicate no change in the mix when the salvaged bituminous is heated to 66° C compared with mixing at the ambient temperature of 28° C (82° F) [t° C = (t° F - 32)/1.8]; 1 kg/m³ = 0.062 lb/ft³; and 1 N = 0.2248 lbf:

Characteristic	3.5 Percent AC 28°C	3.5 Percent AC 66°C	4.5 Percent AC
Proportion bituminous to aggregate	40/60 50/50	40/60 50/50	0/100
Density, kg/m³	234.4 234.1	234.1 235.7	231.8
Stability, N	5843 5718	5945 6163	3832
Voids, %	6.3 6.3	7.2 6.3	7.7
Cold water abrasion loss, %	14.7 12.8	12.9 11.8	14.1

These results compared favorably with those for the conventional mixes that used 4.5 percent AC and virgin aggregate. Some stripping was noted during the test for voids, probably because of loss of bonding characteristics from oxidation of the recycled bituminous mix.

Each mix was tested for asphalt content [t° C = (t° F - 32)/1.8]:

Characteristic	3.5 Percent AC 28°C	3.5 Percent AC 66°C	4.5 Percent AC
Proportion bituminous to aggregate	40/60 50/50	40/60 50/50	0/100
Added AC, % (by weight)	3.5 3.5	3.5 3.5	4.5
Recovered AC, %	4.1 4.2	4.1 4.1	4.6

The recovered asphalt was then tested for penetration and ductility (1 cm = 0.39 in):

Characteristic	3.5 Percent AC 28°C	3.5 Percent AC 66°C	4.5 Percent AC
Penetration	36 60	53 55	82
Ductility, cm	120+ 120+	120+ 120+	120+

PLANT MODIFICATION AND OPERATION

The plant used for this project was a 6.8-Mg (7.5-ton) batch plant with a pug-mill mixer. The plant operation was essentially the same as that for a conventional plant mix except that the aggregate leaving the drier was hotter than normal. The batch plant was modified to feed the cold salvaged bituminous material into the weigh hopper above the pug mill (Figures 5 and 6). The cost of plant modifications was minimal, and the mix was produced without burning the asphalt and thus without smoke pollution.

The quantity of heat added to the aggregate as it moves through the drier must be sufficient to provide a recycled mix that is workable for paving operations. Sufficient heat must be available in the heated aggregate to drive off the moisture in the salvaged bituminous material, melt the old asphalt (thus mixing the old and the new asphalt), and allow for the normal heat losses from the plant operation. On this project, the temperature of the salvaged aggregate as it left the drier was approximately 232° C to 260° C (450° F to 500° F). Figure 7 shows the steps involved in the production of the recycled mixture.

It was planned to produce a recycled mixture with 30 percent salvaged bituminous material and 70 percent salvaged aggregate. However, because some of the salvaged aggregate was used for subgrade corrections, a 50/50 proportion was used for the bulk of the project (all references to proportions or blends of recycled mixtures are for salvaged bituminous material to salvaged or clean aggregate). Even at the 50/50 proportion, enough heat was available to thermally break down the old asphalt mix. Later in the fall, as the weather became colder, a 40/60 proportion was used to get a higher laydown temperature to ensure adequate compaction of the mixture. A 152-m (500-ft) control section of conventional, unrecycled mix was placed on the project for comparison with the recycled mixture.

PAVING OPERATIONS

Paving operations were conventional in all respects except that the recycled bituminous mixture seemed to be "fluffier" than a normal bituminous mixture. The paver screed was raised somewhat to obtain the same compacted thickness as that of a conventional mixture. The plant operator commented that the storage silo would not hold quite as much recycled mixture as conventional mixture according to weight. This appears to be caused by lower than normal mixture temperatures.

The eastbound base was placed in three lifts. The westbound base was placed in one 18-cm (7-in) lift. This was done to hold the heat since the paving was done late in the construction season. A 152-m (500-ft) control section was placed in the eastbound lane for purposes of comparison. Additional asphalt was added to the 3.8-cm (1.5-in) binder or leveling course because it was to carry traffic over the winter months. The final 1.9-cm (0.75-in) taconite-tailings wearing course was placed in the summer of 1977.

TEST RESULTS FOR MATERIALS DURING CONSTRUCTION

Preliminary laboratory tests of the in-place material (samples taken by hand from the road) showed a 3.7 percent asphalt content. The laboratory tests on the crushed

Figure 5. Loading crushed, salvaged bituminous material onto conveyor, which feeds pug-mill stockpile in background.

Figure 6. Point at plant where conveyor feeds cold salvaged bituminous material into pug mill.

Figure 7. Steps involved in production of recycled bituminous material for the Maplewood project.

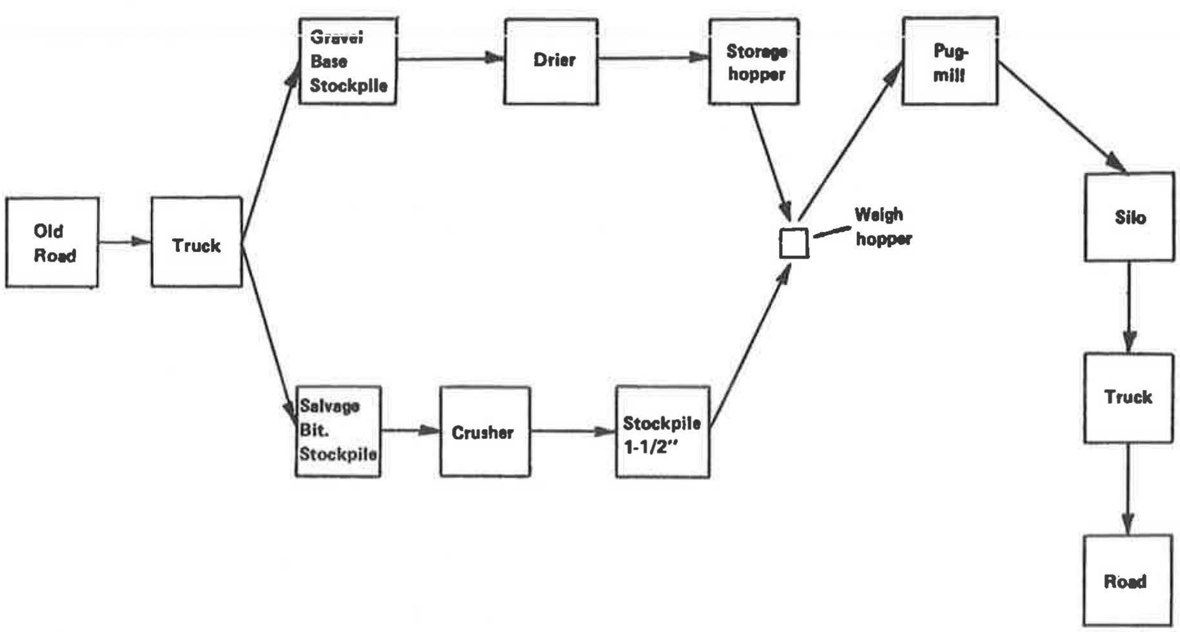

Table 5. Summary of test results: recovered asphalt.

	Recycled Base Mix		Recycled Binder Mix		Cold, Crushed Salvaged Mix	
Property	$\bar{x}$[a]	s	$\bar{x}$[b]	s	$\bar{x}$[c]	s
Bituminous material, percent	4.1	0.36	4.7	0.43	1.9	0.39
Penetration	68	9.75	66	7.72	32	4.02
Ductility, cm	120+	0.00	120+	0.00	120+	0.00
Softening point	123	3.79	123	2.11	138	2.96

Note: 1 cm = 0.39 in.
[a]n = 64. [b]n = 16. [c]n = 27.

Table 6. Summary of test results: new asphalt in storage.

Test	$\bar{x}$	s	n
Original asphalt			
Penetration	128	0.01	21
Ductility, cm	120+	0	16
Absolute viscosity, Pa·s	67.8	19.25	14
Thin-film oven[a]			
Loss on heating, percent	0.42	0.03	16
Penetration of residue	69	1.77	16
Percentage of original penetration	54	1.77	16
Ductility of residue, cm	120+	0	16

Note: 1 cm = 0.39 in; 1 Pa·s = 10 poises; t°C = (t°F - 32)/1.8; 1 mm = 0.039 in.
[a]At 163°C, 3.2 mm, 5 h.

Table 7. Sieve analysis of salvaged aggregate at plant site.

	Percentage Passing				
	Cold Feed		BA-2 Specification[c]	Hot Bins (composite)[d]	
Sieve Size[a] (mm)	$\bar{x}$[b]	s		$\bar{x}$[e]	s
19	97.4	1.21	100	99.5	0.78
16	94.5	1.52	95-100	97.3	1.73
9.5	83.6	2.59	65-95	87.5	1.10
4.75	70.9	3.26		77.1	1.39
2.00	60.6	3.15	35-65	66.2	3.32
0.425	32.2	3.04	10-35	35.5	3.12
0.075	6.78	2.08	1-7	6.21	1.56

[a]Corresponding U.S. sieve sizes: 0.75, 0.625, and 0.375 in and nos. 4, 10, 40, and 200.
[b]n = 24.
[c]Current Minnesota DOT gradation specification for aggregate used in bituminous mixtures.
[d]The heated, dried aggregate in this plant is split into three segments going into storage bins—coarse, intermediate, and fine—by using the 19-, 16-, and 4.75-mm (0.75-in, 0.625-in, and no. 4) sieves. It is then recombined at batching time according to requirements.
[e]n = 24.

salvaged material produced by the contractor and ready for recycling showed only 1.9 percent asphalt content. This difference is explained by the amount of gravel base mixed with the material during scarifying and loading operations. This was borne out by the results of tests run on mix samples taken during paving (Tables 5 and 6). The 50/50 recycled mix with 3 percent new asphalt AC-1 (120/150) had an extracted asphalt content of 4.1 percent. The 40/60 recycled mix with 3.5 to 4 percent new asphalt AC-1 (120/150) had an extracted asphalt content of 4.7 percent.

Table 5 gives the results of tests on the recovered asphalt. These were compared with the results of tests run on the new asphalt used in the mixes (Table 6). It was considered highly desirable, as a gauge of oxidation, that the penetration values of 66 and 68 for the asphalt extracted from the recycled mixture be close to the penetration value of the new asphalt (using the thin film oven test result of 69).

Table 8. Summary of test results for hot mix.

	Base Mix		Binder Mix	
Property	$\bar{x}$[a]	s	$\bar{x}$[b]	s
Marshall density, kg/m³	236.0	1.79	236.6	3.14
Marshall stability, N	6978	1205.1	6230	966.5
Voids, Rice method, percent	6.4	1.27	5.1	1.81
Cold-water abrasion loss, percent	8.7	2.19	6.6	2.91

Note: 1 kg/m³ = 0.062 lb/ft³; 1 N = 0.225 lbf.
[a]n = 58. [b]n = 13.

Table 9. Sieve analysis of aggregate recovered after extraction: recycled hot mix.

	Percentage Passing					
	All Samples		Base Samples		Binder Samples	
Sieve Size[a] (mm)	$\bar{x}$[b]	s	$\bar{x}$[c]	s	$\bar{x}$[d]	s
19	99.9	0.80	99.8	0.89	100.0	0.00
16	97.5	1.97	97.4	2.05	98.1	1.50
9.5	87.4	3.04	87.3	3.14	87.9	2.60
4.75	75.8	3.47	75.5	3.42	77.1	3.50
2.00	64.3	2.34	63.9	3.56	65.7	3.20
0.425	35.4	3.31	35.1	3.49	36.4	2.22
0.075	9.66	1.40	9.63	1.79	9.77	0.60

[a]Corresponding U.S. sieve sizes: 0.75, 0.625, and 0.375 in and nos. 4, 10, 40, and 200.
[b]n = 71.
[c]n = 58.
[d]n = 13.

The objective was to recycle the gravel base as it came off the road and the processed salvage bituminous as stockpiled. Gradations of the gravel base were taken to determine if the materials were uniform going into the dryer. The results show that the material was uniform. They were also near compliance with the bituminous aggregate specification except for the minus 0.075-mm (no. 200) material. Gradation summaries and the bituminous aggregate specification are given in Table 7.

As noted in Table 8, the hot mix produced with these salvaged materials, by this method, exhibits the qualities called for in a full-depth bituminous base. The resultant mean values in the mix of 4.1 percent asphalt content and 6.4 percent voids are within a tolerable variance of the design criteria of 4.5 percent asphalt content and 4 to 6 percent voids. The results of the Marshall tests for density and stability are more than adequate at 235.5 kg/m³ (14.6 lb/ft³) and 6978 N (1570 lbf) respectively. The test results indicate that there is little difference in quality between the base and the binder. The sieve analysis of the aggregate recovered from the hot-mix samples is summarized in Table 9. These test results show that there is variance from sample to sample—probably a result of using the materials from the road without controls for uniformity.

TEST RESULTS AFTER PAVING

Pavement cores, Benkelman beam deflections, and a crack survey were taken before the final wearing course was placed. In general, the tests indicated that the base constructed with recycled mix was comparable to base constructed with conventional mix.

Cores were taken from the roadbed shortly after paving. These cores were taken at locations where samples had been taken during paving. The average test

Table 10. Laboratory test results for road cores (recycled mixtures): bituminous mixture and recovered asphalt.

Test	Base Cores $\bar{x}$[a]	Base Cores s	Binder Cores $\bar{x}$[b]	Binder Cores s
Bituminous mixture				
Marshall density, kg/m^3	227.0	5.24	222.7	6.22
Voids, Rice method, percent	9.9	1.95	10.6	3.71
Bitumen, percent	4.0	0.23	5.1	0.54
Recovered asphalt				
Penetration	54	7.34	52	6.85
Ductility, cm	120+	0.00	120+	0.00
Softening point	127	3.21	129	4.31

Note: 1 kg/m^3 = 0.062 lb/ft^3; 1 cm = 0.39 in.
[a]n = 24. [b]n = 7.

Table 11. Laboratory test results for road cores (recycled mixtures): sieve analysis of recovered aggregate.

Sieve Size[a] (mm)	Percentage Passing: All Cores $\bar{x}$[b]	All Cores s	Base Cores $\bar{x}$[c]	Base Cores s	Binder Cores $\bar{x}$[d]	Binder Cores s
19	99.7	0.62	99.7	0.56	99.6	0.89
16	97.2	1.52	97.0	1.50	98.2	1.30
9.5	86.5	3.31	86.1	3.51	88.0	1.87
4.75	75.0	3.89	74.6	4.25	76.4	1.14
2.00	63.0	3.69	62.7	4.03	64.4	1.14
0.425	34.7	2.68	34.4	2.75	36.0	2.12
0.075	9.53	0.86	9.49	0.84	9.68	1.03

[a]Corresponding U.S. sieve sizes: 0.75, 0.625, and 0.375 in and nos. 4, 10, 40, and 200.
[b]n = 26.
[c]n = 21.
[d]n = 5.

values and their standard deviations are given in Tables 10 and 11.

Marshall stability tests could not be run on the cores taken from the road because of their diameter and the roughness of the sidewall. However, many of the cores were tested by triaxial compression to determine the resilient modulus of the unconfined cores. The results show the recycled mix to have a lower modulus than historical data gathered on several state highways in Minnesota. It is a reasonable modulus and not unusual for conventional mixes. This resilient modulus indicates a more flexible pavement and one with more voids. Data gathered by the bituminous office of the Minnesota DOT verify that statewide nonwearing courses have about 9 percent voids compared with 10 percent on this project.

In June 1977, after the binder course had carried traffic over the winter, Benkelman beam deflections were run on the road surface before the wearing course was placed. The deflections were taken at approximately 152-m (500-ft) intervals throughout the length of the recycled paving. An additional three locations were tested in the 152-m conventional section. In the evaluation of these deflections, there is a slight difference between the eastbound roadway where the base was placed in three lifts and the westbound roadway where the base was placed in one lift. The westbound roadway has slightly higher deflections, greater range, and larger deviation. Despite this, the average deflections of the three sections are similar:

Test Site	Number of Tests	$\bar{x}$	s
Eastbound, recycled	9	0.46	0.09
Eastbound, conventional	3	0.48	—
Westbound, recycled	10	0.51	0.10
All		0.51	0.09

When these deflections are evaluated according to criteria developed in Minnesota DOT investigation 183 (Application of AASHO Road Test Results to Flexible Pavement Design in Minnesota) and investigation 195 (Full-Depth Asphalt Pavement Structures Evaluation), a total "gravel equivalency" of about 23 is the result. A unit gravel equivalency of 2.7 can then be calculated for the base and binder. An R-value of 75 for the sand and gravel subgrade was assumed. The conventional section, which is limited in length, and the eastbound roadway behave as would be expected for 23.4 cm (9.2 in) of full-depth asphalt base. The westbound roadway behaves similarly but is not quite as strong; it compares with 2.18 cm (8.6 in) of conventional full-depth asphalt base. The strength is equal to or greater than the design thickness of 21.6 cm (8.5 in).

In a crack survey made in June 1977, the only cracks noted were in the eastbound roadway. This appears to be a result of the different methods of paving (multiple lift as opposed to single lift). Five full-width cracks and one that crossed one traffic lane and the turn lane were noted. All cracks were at catch basins, electrical "pull boxes," or where some sort of utility passed under the road.

APPLICATION OF METHOD TO OTHER CONVENTIONAL PLANTS

Although this method of pavement recycling was developed for use at a batch plant, the Minnesota heat-transfer concept can also be applied to conventional dryer-drum and continuous-mix plants. Several equipment manufacturers have modifications for drum mixers and batch plants. Some contractors have made modifications to their plants. The only limitations appear to be the minimal proportion of clean aggregate, which is used as the heat-transfer medium, and the maximum teperature of the dryer. Contractors appear to be reluctant to increase the temperature of the aggregate leaving the dryer to more than 260° C (500° F).

BENEFITS OF RECYCLING

Observations to date indicate that it is feasible to produce a hot bituminous mixture by following the method described in this paper and using recycled bituminous material and aggregate. The recycled hot mix can be placed by conventional methods and appears to be similar to a conventional mix.

The benefits of this process are

1. Its use of conventional equipment with minor modifications,
2. Reuse of all aggregates,
3. Reuse of the old asphalt as an effective binder,
4. Use of less new asphalt,
5. Fuel savings,
6. Minimal cost for plant modifications,
7. Normal or nearly normal production rates, and
8. Process emissions that are within pollution standards.

GUIDELINES FOR DETERMINING FEASIBILITY OF RECYCLING OLD BITUMINOUS PAVEMENT AND AGGREGATE BASE

To determine the cost saving of reclaiming an old bituminous pavement, the following should be known:

1. The amount of asphalt in the old bituminous pavement by the extraction method or by using 80 percent of the actual asphalt used when the pavement was constructed;
2. The cost of new asphalt;
3. The cost of aggregate (BA-2) for bituminous mixture;
4. The cost of salvaging, loading, hauling, and stockpiling existing aggregate base;
5. The cost of scarifying, loading, hauling, stockpiling, and crushing salvaged bituminous pavement; and
6. The cost or profit of disposing of the existing gravel base and bituminous pavement [this should include scarifying, loading, hauling, leveling, landscaping, and the cost of dumping (royalty) or may include payment for the material being dumped].

Hauling costs are a major factor in determining the cost of a project. A preferred method for determining hauling costs is the cycle time method. The following information is needed: (a) rental rate of hauling unit per hour, (b) capacity of hauling unit, (c) cycle time of hauling unit. This can be expressed as (rental rate × cycle time) ÷ (capacity × 60) = cost per megagram. For example, if rental rate = \$26/h operated, capacity = 15.5 Mg, and cycle time = 45 min, then (26 × 45)/(15.5 × 60) = \$1.25/Mg.

Hauling costs can be reduced significantly on recycling projects by backhauling salvaged bituminous material and salvaged gravel base.

CONCLUSIONS

The Minnesota heat-transfer concept has wide application for cost-effectively recycling old bituminous pavements and aggregate bases. The modification to conventional batch, drum-mixer, and continuous-mix plants is minimal. This method requires clean aggregate for heat transfer, which in turn requires additional new asphalt. By using additional asphalt with higher than normal penetration, the effective penetration of the recycled asphalt binder is improved without the use of rejuvenators. The production rate of the plant is not seriously reduced. No smoke is emitted from the modified batch plant operation. There are some smoke emissions from the modified drum-mixer operation, but this can be held within present pollution standards. Although no continuous-mix plants have actually been modified, it is felt that they would work much like a modified batch plant.

Practical proportions for the design of future recycling projects would appear to be 50/50 for batch and continuous-mix plants. Since there appears to be some additional heat in the modified drum-mixer plants, the practical proportion limit would appear to be 60/40.

Many roadways, streets, and airports have been constructed with several centimeters of bituminous surfacing and several centimeters of gravel base. In many cases, no new aggregates would be required to produce a recycled mix that would result in a higher strength structure. Only the addition of new asphalt would be required, and this would be less than that required for a new conventional mixture.

Although there is some question as to the durability of recycled mix versus new conventional mix, all conventional testing shows recycled mix to be comparable to new mixes.

If the salvaged bituminous material and the salvaged aggregate are uniform and well graded, the gradation of the recycled bituminous mixture will also be uniform and well graded provided the contractor uses reasonable care in handling the stockpiled materials. The only change in gradation is the slight increase in the amount of materials passing the 0.075-mm (no. 200) sieve.

The savings attributed to recycling seem to be positive in all cases. Even if recycling were equal in cost to conventional construction, there are environmental and social benefits of extending and preserving the nonrenewable asphalt and aggregate resources. The biggest challenge left is to make recycling work for us by looking at every project to determine if the benefits of recycling are positive.

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Determination of Moisture Contents in Bituminous Mixtures by a Nuclear Method

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A study undertaken to evaluate the effect of moisture on nuclear-gauge data and to explore whether the nuclear gauge can be used to determine moisture content when asphalt content is held constant in a paving mixture is reported. A Troxler model 2226 gauge was used in the study. Four wearing-course mixtures that contained slag, gravel, and limestone aggregates were studied, and moisture content was varied from 0 to 3.47 percent. Statistical analysis of the