2. Based on the findings of this study and the experience and findings of others, it is felt that satisfactory mixtures can be produced by using the dryer drum. The only question relates to the effect of moisture, and it would appear from previous experience that moisture produces little if any adverse effect.

3. An increase in mixing and compaction temperature caused a decrease in resilient Poisson's ratio but did not have any significant effect on tensile strength, static and resilient modulus of elasticity, and static Poisson's ratio. There was an indication that fatigue life was improved by an increase in mixing temperature up to a certain stress level. However, the asphalt content also varied slightly.

ACKNOWLEDGMENT

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The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

REFERENCES

1. A. S. Adedimila and T. W. Kennedy. Fatigue and Resilient Characteristics of Asphalt Mixtures by Repeated-Load Indirect Tensile Test. Center for Highway Research, Univ. of Texas at Austin, Res. Rept. 183-5, Aug. 1975.
2. M. Rodriguez and T. W. Kennedy. The Resilient and Fatigue Characteristics of Asphalt Mixtures Processed by the Dryer-Drum Mixer. Center for Highway Research, Univ. of Texas at Austin, Res. Rept. 183-8, Dec. 1976.
3. B. W. Porter and T. W. Kennedy. Comparison of Fatigue Test Methods for Asphalt Materials. Center for Highway Research, Univ. of Texas at Austin, Res. Rept. 183-4, April 1975.
4. D. Navarro and T. W. Kennedy. Fatigue and Repeated-Load Elastic Characteristics of Inservice Asphalt-Treated Materials. Center for Highway Research, Univ. of Texas at Austin, Res. Rept. 183-2, Jan. 1975.

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Evaluation of Oregon's First Project in Hot-Mix Asphalt Recycling

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Pavement recycling has been suggested as a workable alternative to more conventional methods of pavement rehabilitation and a means of offsetting some of the problems that result from spiraling energy costs and shortages of raw materials. The Woodburn asphalt recycling paving project, Oregon's first experience with using a hot-mix process in large-scale recycling of asphalt concrete, is discussed. The project is described, overlay and mix designs are indicated, the construction program and the specific equipment used are reviewed, the program of materials sampling and testing and data collection is described, and test results are summarized. Special emphasis is given to an investigation of possible changes in material properties through the construction process. A summary is presented of the factors that most affect the production of emissions. Costs and fuel consumption are examined, and possible savings over a similar, conventional paving project are highlighted. Specific recommendations are presented for the benefit of other agencies that are considering similar projects, and future research needs are outlined.

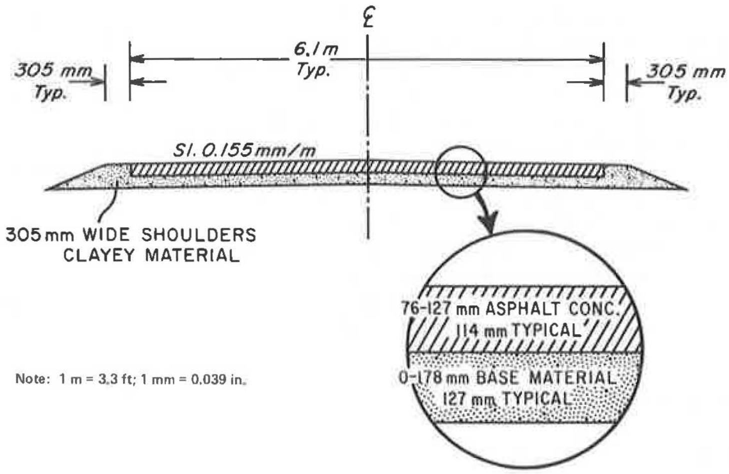
The need to reduce fuel consumption and conserve natural resources has been an item of ever-increasing importance during recent years. In 1976, the highway division of the Oregon Department of Transportation (DOT) was faced with the problem of disposing of nearly 45 000 Mg (50 000 tons) of asphalt concrete pavement placed for temporary purposes in the rehabilitation of I-5 between Salem and Woodburn. Officials of the division recognized the possibility of using this asphalt concrete as raw material for recycling and, with the assistance of federal funding through Region 15 of the Federal Highway Administration (FHWA), a demonstration project that became known as the Woodburn asphalt pavement recycling project was initiated.

To fulfill the objectives of the national demonstration project program for asphalt pavement recycling, a comprehensive work plan was developed that specified the responsibilities of the highway division through the project's duration. Included in the plan was a program for sampling, testing, and evaluation before and during construction. In addition, provision was made for post-construction testing and evaluation to continue for years to come.

This paper discusses the results of the investigations performed by the highway division of the Oregon DOT in fulfilling its responsibilities through the first year of project evaluation. Specifically, the objectives of this paper are to

1. Present a description of the project, including its location, overlay thickness design, asphalt concrete mix design, and final mix specifications;
2. Indicate the final construction procedure and equipment used;
3. Describe the program of materials sampling and testing and collection of data on weather, pollutant

Figure 1. Typical roadway section from Woodburn project before rehabilitation.



Note: 1 m = 3.3 ft; 1 mm = 0.039 in.

Table 1. Pavement deflection measurements for Woodburn recycling project.

		Deflection* (mm)		
Section Stations	Traffic Lane	Mean	Standard Deviation	Coefficient of Variation
89+00 to 96+50	Eastbound	1.09	0.25	0.23
115+50 to 123+00	Westbound	1.02	0.36	0.35
132+00 to 139+50	Eastbound	0.97	0.23	0.24
166+50 to 174+00	Westbound	1.14	0.30	0.27
192+00 to 199+50	Eastbound	0.69	0.23	0.33
220+50 to 228+00	Westbound	0.97	0.18	0.18
253+00 to 260+50	Eastbound	1.37	0.58	0.43
271+50 to 279+00	Westbound	1.09	0.43	0.40
288+00 to 295+50	Eastbound	1.12	0.330	0.30
318+50 to 326+00	Westbound	1.19	0.46	0.38
358+00 to 365+50	Eastbound	1.22	0.30	0.25
371+50 to 379+00	Westbound	1.27	0.76	0.60
409+00 to 416+50	Eastbound	1.19	0.53	0.45
429+50 to 437+00	Westbound	0.97	0.23	0.24
474+00 to 481+50	Eastbound	1.19	0.28	0.24
481+50 to 489+00	Westbound	1.30	0.45	0.34

Note: 1 mm = 0.039 in; t°C = (t°F - 32)/1.8.
*Adjusted to pavement temperature of 21°C.

emissions, costs, and energy use;

4. Present the results of materials tests and highlight any changes in the properties of materials through the construction process;
5. Document the levels of pollutant emissions reported during the project and indicate factors that seemed to affect the increase or decrease of opacity and particulates;
6. Present a summary of the costs and energy consumption of the project and indicate possible savings in comparison with a conventional asphalt concrete paving project; and
7. Present recommendations that may be useful to other agencies that are considering similar projects and draw final conclusions.

DESCRIPTION OF THE PROJECT

Location

The Woodburn recycling project consisted of widening and overlaying a 16-km (10-mile) section between Woodburn and St. Paul on the Hillsboro-Silverton Highway, a state secondary highway located in Marion County, Oregon.

Cross Sections and Overlay Design

Investigations were conducted early in the project to determine the characteristics of the pavement to be overlaid. Before reconstruction, the highway had an asphalt concrete surface 6.1 to 7.3 m (20 to 24 ft) wide. A sample of eight cores was obtained. Results of tests on those cores indicated that the thickness of the surface wearing course ranged from 76 to 127 mm (3 to 5 in) and the thickness of the base course ranged from 0 to 178 mm (0 to 7 in). Average values for surface- and base-course thicknesses were 114 and 127 mm (4.5 and 5 in), respectively, as shown in Figure 1.

In February of 1977, a Benkelman beam inventory was conducted to develop an overlay thickness design and to document any changes in deflection that resulted from the placement of a known thickness of recycled asphalt concrete. The mean and standard deviation of the temperature-corrected deflections for each 228.6-m (750-ft) study section are given in Table 1.

As a result of these investigations, a 152-mm (6-in) thick overlay design was developed. Two 3.7-m (12-ft) travel lanes were provided; these lanes had paved shoulders between 305 and 610 mm (1 and 2 ft) wide for an overall pavement width of 7.9 to 8.5 m (26 to 28 ft). The overlay was to be placed over the entire width of the pavement in two 76-mm (3-in) lifts. This postconstruction cross section is shown in Figure 2 (1).

Preliminary Specifications

The specific job-mix formula originally used in producing the now recycled material consisted of the following gradations (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing by Total Weight of Mix
19-6	34.8
6-2	28.7
2-0	30.9

The original 5.6 percent asphalt content was later changed to 6.0 percent because of high voids.

Prior to advertising the project for bidding, highway division engineers estimated the possible range of proportions of crushed asphalt concrete, new aggregate, and new asphalt cement that would be likely to achieve a desirable mixture. Based on experience in past recycling projects, the following proportions and their corresponding tolerances were specified:

Component	Percentage by Total Weight of Mix	Tolerance (%)
Crushed asphalt concrete	78-100	±4
Additional 19x2-mm aggregate	0-20	±4
Additional asphalt cement	0-2	±0.5

In addition, gradation specifications for both the crushed asphalt concrete and the virgin aggregate were developed:

Material	Sieve Size (mm)	Percentage Passing by Weight
Crushed asphalt concrete	51	100
	19	50-90
	2	0-15
Virgin aggregate	25.4	100
	10	95-100
	6	25-50
	2	0-19
	0.074	0-4

The 50-mm (2-in) maximum size indicated for the crushed asphalt concrete was specified to achieve thorough heating of all of the particles. The 19-mm (0.75-in) and 2-mm (No. 10) gradations for the crushed asphalt concrete were specified to minimize the possibility of fracturing the aggregate in the old asphalt concrete and thus minimize the production of new fines. The gradations for the virgin aggregate were specified to ensure that there would be a sufficient percentage of voids in the mix.

Mix Design

The final specifications required the contractor to provide representative samples of crushed material 15 days before producing any mixture for use. The materials section of the Oregon DOT undertook a mix design study on these samples in which the Oregon mix design procedure (modified Hveem method) (2) was used to determine the proper amounts of asphalt and 19×2-mm (0.75 in × No. 10) virgin aggregate that should be added to the crushed material to achieve the highway division's design criteria, which are given below:

Property	Surface	Base	Shoulder
Stability (minimum S-value)			
First compaction	30	30	30
Second compaction	30	–	–
Air voids (%)	≈4	≈2	≈2
Minimum wet strength retained (%)	70	70	70
Film thickness	Sufficient	Sufficient	Sufficient

At times, all criteria could not be met and engineering judgment was used in determining the recommendations. A summary of the recommended asphalt additions and corresponding mix properties for mixes that contained 100, 90, and 80 percent recycled asphalt concrete (concretes 1, 2, and 3) is given in Table 2.

Note that, since the recycled mix was relatively new and ductile, satisfactory results were obtained without the addition of any softening agent.

In addition to the tests to determine mix properties, penetration and viscosity tests were run on the recovered asphalt before and after the addition of different grades and percentages of asphalt cement. Few tests were conducted, however, and the results were inconclusive.

Field Variation of Job-Mix Proportions

Once actual construction began, there were several significant deviations from the recommendations cited above. In Figure 3, the amounts of new asphalt and virgin aggregate recommended by the mix designs for surface and base courses are represented by the solid lines. The broken lines represent extrapolations of the mix design to include a 30 percent addition of virgin aggregate. The large dots shown represent actual mix proportions used during construction operations. All of the proportions include more asphalt than was originally recommended, and the 30 percent addition of aggregate, although not laboratory tested, was used extensively in the field.

The effort to reduce opacity and particulate emissions was mainly responsible for this departure from the recommendations. It was discovered early in the project that pollutant emissions decreased when more virgin aggregate was introduced and also when mixing was done at lower temperatures inside the drum. Higher asphalt contents were necessary at these lower temperatures to maintain good workability.

The possibility that the sample of crushed asphalt concrete used in the mix design was not representative could also account for some of the variation. In the sample obtained for the mix design, the initial asphalt content of the 100 percent recycled mix was 5.6 percent. The average asphalt content of the samples of crushed asphalt concrete obtained during construction was only 4.6 percent. The range of final asphalt contents after the addition of new asphalt cement in the mix design was 5.1-5.6 percent for the base course. Even though more new asphalt was added in mixing operations in the field, the final average asphalt content was 5.4 percent for 23 samples of the top lift and 5.8 percent for 23 samples of the bottom lift. This is very close to that obtained in the mix design after the addition of new asphalt cement.

In addition to the combinations used during construction (Figure 3), a combination of 1.5 percent Shell AR-1000 with 20 percent 19×2-mm (0.75-in × No. 10) aggregate was tried. In addition, 30 percent 6×2-mm (0.25-in × No. 10) aggregate was used with 2.1 percent AR-2000 asphalt. The use of these materials was discontinued because (a) the mix that incorporated the AR-1000 asphalt yielded unacceptable levels of pollutant emissions and (b) the 6×2-mm aggregate did not perform better than the 19×2-mm aggregate and was more costly. Consequently, except for these experiments, AR-2000 asphalt cement and 19×2-mm aggregate were used throughout the project.

CONSTRUCTION PROCEDURES AND EQUIPMENT

In the final construction procedure used in mixing and placing the recycled asphalt concrete, the stockpiled old asphalt concrete was first crushed to the desired aggregate specification by using equipment arranged in the configuration shown in Figure 4. This configuration was adopted after a comprehensive series of experiments in the laboratory, in a commercial crushing plant, and on site before the initiation of paving operations. The material was fed into the crusher by one D-8H crawler tractor equipped with rippers. An additional D-6 crawler tractor was used intermittently during the job, usually for a total of 2 h/day.

The crushed asphalt concrete was then stockpiled. To avoid any problems of "healing together" in the stockpile, the crushing rate was coordinated with the final material production rate to minimize the time that the

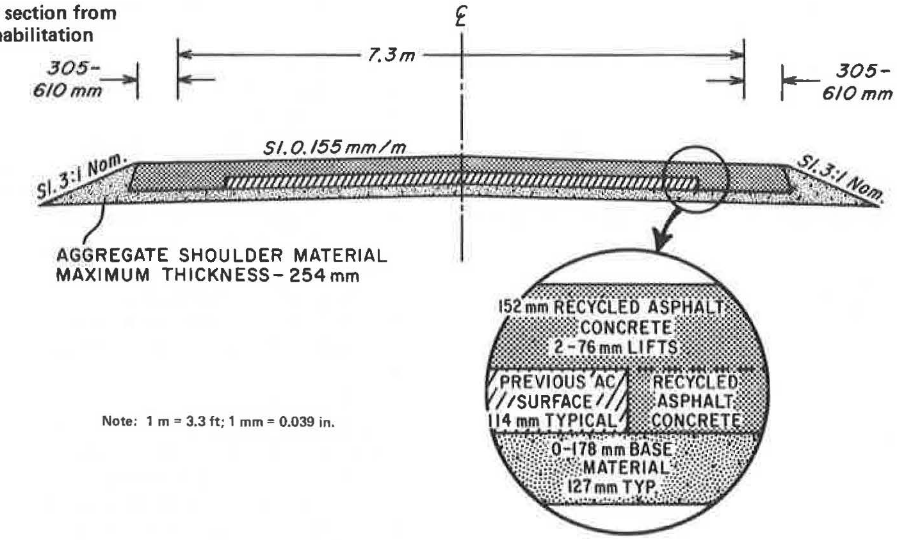


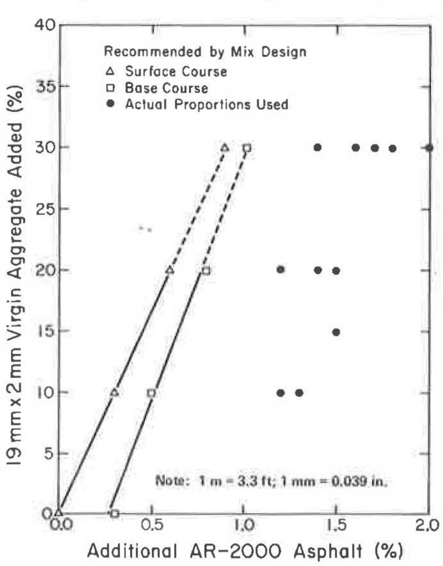
Figure 2. Typical roadway section from Woodburn project after rehabilitation with recycled asphalt concrete.

Table 2. Mix properties at recommended additions of new asphalt.

Item	Mix 1[a] Surface	Mix 1[a] Base	Mix 2[b] Surface	Mix 2[b] Base	Mix 3[c] Surface	Mix 3[c] Base
Asphalt (%)						
Content in crushed recycled pavement[d]	5.6	5.6	5.0[e]	5.0[e]	4.5[e]	4.5[e]
Recommended addition	0.0	0.3	0.3	0.5	0.6	0.8
Final content	5.6	5.9	5.3	5.5	5.1	5.3
Mix property						
S-value						
First compaction	30.0	27.0	33.2	32.0	32.6	31.8
Second compaction	36.0	19.8	36.2	27.0	35.6	34.8
Air voids (%)						
First compaction	5.7	4.7	4.3	3.7	4.9	4.3
Second compaction	2.8	1.8	2.6	2.0	2.8	2.0
Bulk specific gravity						
First compaction	2.32	2.33	2.35	2.36	2.35	2.36
Second compaction	2.39	2.40	2.39	2.40	2.41	2.42
Cohesiometer value (C), first compaction	572	648	863	878	485	471

Note: 1 mm = 0.039 in.
[a] One-hundred percent recycled asphalt concrete.
[b] Ninety percent recycled asphalt concrete and 10 percent 19x2-mm virgin aggregate.
[c] Eighty percent recycled asphalt concrete and 20 percent 19x2-mm virgin aggregate.
[d] Percentage by total weight of mix.
[e] Asphalt content in 100 percent recycled asphalt concrete x percentage of recycled asphalt concrete in mix.

Figure 3. Additions of asphalt recommended in mix design and additions of asphalt actually used.

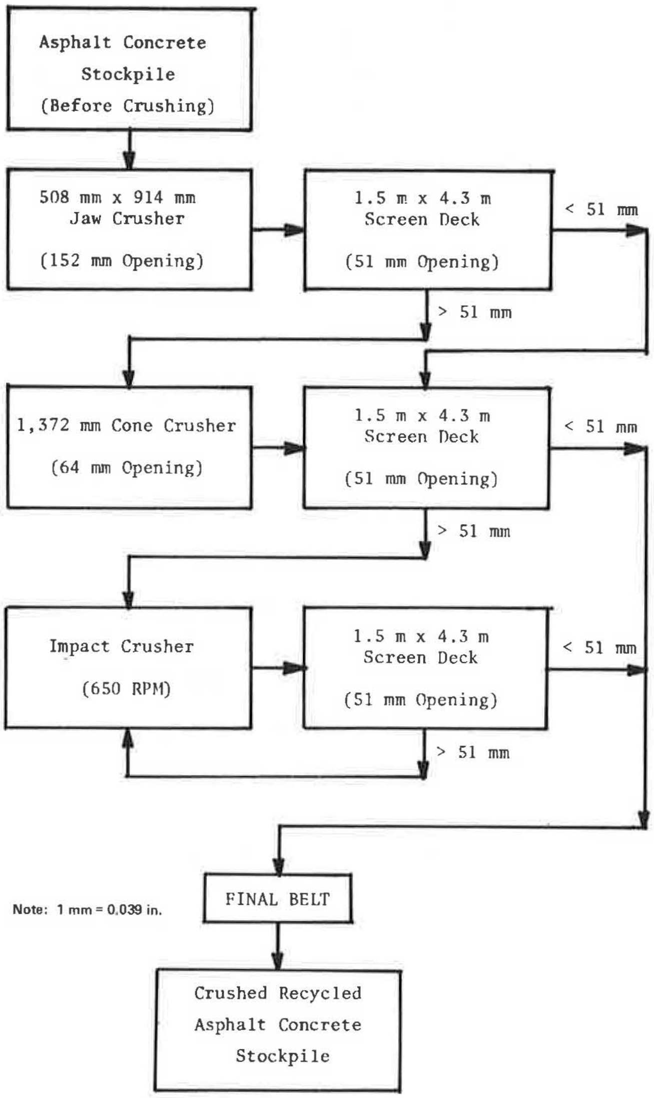


old asphalt concrete remained in the crushed stockpile. The crushed material was picked up with a Cat 980 loader and placed in two of three cold-feed hoppers. The third cold-feed hopper was reserved for virgin aggregate. Proper proportioning of aggregate and old asphalt concrete was accomplished through the use of two Ramsey belt scales, one that weighed new aggregate and one that weighed the blend of crushed asphalt concrete and virgin aggregate.

Water was then added for the purpose of reducing the emission of fine particulates. This was accomplished through the use of a spray bar mounted over the conveyor leading to the drum dryer. This bar was equipped with pressure gauges so that water could be added in known percentages.

A dryer-drum plant manufactured by Boeing Construction Company, with a capacity of 363 Mg/h (400 tons/h), was used to heat and mix the recycled asphalt-aggregate blend with new asphalt. The plant was modified by using the Pyrocone combustion control system developed by Boeing. The burner was set back from the drum, and a stainless steel cylinder was used to conduct the heat to the drum. The Pyrocone, a metal cone perforated with 25-mm (1-in) diameter holes, was placed between the burner and the entrance to the drum

Figure 4. Configuration of final crushing operation.



Note: 1 mm = 0.039 in.

to allow heat transfer and at the same time provide a barrier between the flame and the recycled material. A high-speed conveyor was also used to feed the cold material into the drum so as to "throw" the material farther from the heat. A steel baffle 4.3 m (14 ft) from the rear of the drum that covered all but 254 mm (10 in) around the perimeter of the drum's inside diameter helped to control dust (3, 4).

The mix was hauled to the paving site by 15.4-m^3 (20-yd^3) capacity "belly" dump trucks. A windrow of mix was placed a short distance ahead of the Blaw-Knox 220 rubber-tired paver equipped with a slat conveyor pickup machine. Breakdown rolling was accomplished by using an 11-Mg (12-ton) Bomag 220-A vibrator roller. A Buffalo three-leg steel-wheel roller that weighed 12 Mg (13 tons) was used for intermediate rolling; finish rolling was accomplished by use of a 9-Mg (10-ton) Ray-Go vibrator roller, which rolled only static (the vibrating mechanism was not in use, and the roller was being operated as a conventional roller).

SAMPLING AND TESTING OF MATERIALS

As part of the demonstration project, the highway division conducted an ambitious program of sampling and testing of materials during and after construction. The locations of sampling relative to the various construction processes are shown in Figure 5.

Pavement cores were also obtained and tested after completion of paving operations. The battery of tests performed on each of the sample types is given in Table 3.

DATA COLLECTION

In addition to the program of materials sampling and testing, a major effort was made to document information on weather (including temperature and humidity), levels of emissions, plant production rates, mix temperatures, and fuel consumption and costs.

RESULTS OF MATERIALS TESTS

Gradation

The gradation of the crushed asphalt concrete before removal of the asphalt is shown in Figure 6. The shaded area represents the gradation specifications for this material. No problem was encountered in meeting the specifications except for the material passing the 2-mm (No. 10) screen (the specification was exceeded in 58 percent of the samples tested, but in those samples the amount passing the 2-mm sieve never exceeded 18 percent).

Figure 7 compares the average gradations of the aggregate materials in the recycled asphalt concrete before and after crushing. As the figure shows, the aggregate in the recycled asphalt concrete was finer after crushing, which indicates that both aggregate particles and asphalt-aggregate chunks were fractured. It is uncertain at this point whether this fracturing was caused by the crushing process or the action of the equipment as it worked on the stockpile.

The average gradations of the aggregate material at the final belt and at the street after additions of 20 and 30 percent 19×2-mm (0.75-in × No. 10) virgin aggregate are shown in Figure 8. The figure indicates that there was little difference in the aggregate gradations after the addition of 20 or 30 percent 19×2-mm virgin aggregate. The material with 20 percent additional virgin aggregate is finer in the 6-mm (0.25-in) to 0 sizes.

Both blends are significantly coarser than the aggregate material at the final belt. Again, this would be expected because of the addition of the 19×2-mm (0.75-in × No. 10) aggregate. Note, however, that the percentage passing the 0.075-mm (No. 200) sieve does not differ significantly although it is slightly higher for the material at the final belt than for the blends.

Properties of Recovered Asphalt

Average values for the properties of recovered asphalt in samples taken in the stockpile and at the final crusher belt are given in Table 4. Table 4 also gives the average properties of recovered asphalt for 11 combinations of asphalt and virgin aggregate added to the recycled asphalt concrete. Again, as expected, greater additions of asphalt led to the lower viscosities and higher rates of penetration in the recycled asphalt concrete mixture. Note also that the crushing operation did not seem to affect the properties of the recovered asphalt at all.

Properties of Asphalt Mix

Table 4 also gives the average results of tests to determine asphalt mix properties. These results display the highest degree of variability, and it is difficult to come to any general conclusions about the effect of the various construction processes on the mix properties.

Statistically, there is a significant difference (α = 1 percent) in the means for samples obtained at the stockpile before crushing and at the final belt after crushing for the following tests (5): (a) bulk specific gravity (first and second compaction), (b) Hveem stabilometer (second compaction), and (c) percentage air voids. Since the properties of recovered asphalt were not affected by crushing, it would appear that the mix properties were probably affected by the change in aggregate gradation.

Inspection of the results from box samples obtained at the street shows a significant number of combinations of asphalt and virgin aggregate that do not yield satisfactory mixes from the standpoint of the design criteria for stability and air voids. These problem mixes include the following combinations:

Additional Asphalt (%)	Virgin Aggregate (%)
1.2	10
1.5	15
1.5	20
1.7	20
2.1	30

Figure 5. Location of sampling sites in Woodburn construction operation.

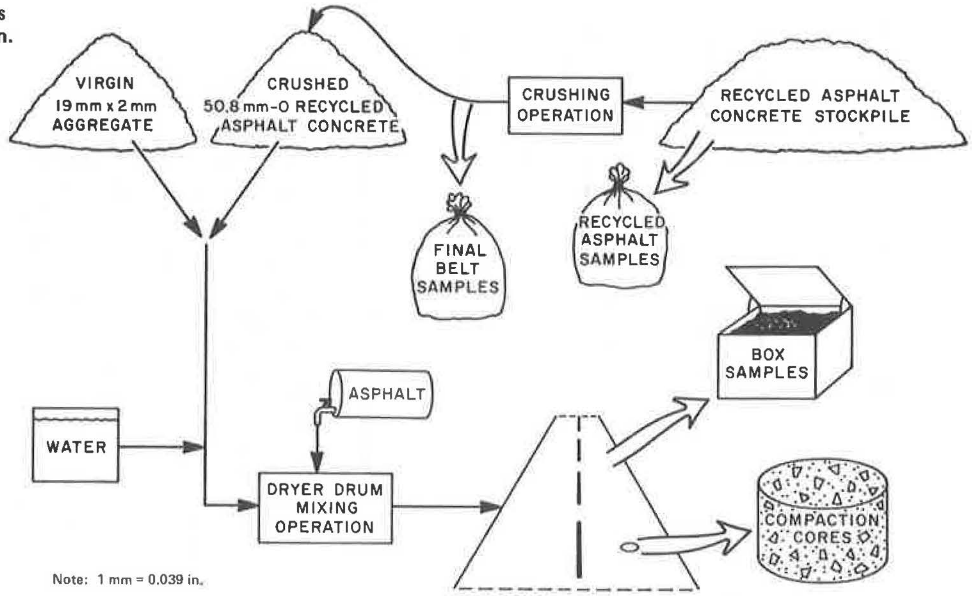


Table 3. Tests performed on sample types during and after construction.

Type of Test	During Construction: Recycled Asphalt Concrete: From Stockpile Before Crushing	From Final Belt After Crushing	Box Samples	Compaction Cores	Pavment Cores (after construction)[a]
Aggregate properties	Gradations before and after asphalt removal	Gradations before and after asphalt removal	Gradations after asphalt removal	—	Gradations after asphalt removal
Properties of recovered asphalt	Asphalt content Penetration Kinematic viscosity Absolute viscosity	Asphalt content Penetration Kinematic viscosity Absolute viscosity	Asphalt content Penetration Kinematic viscosity Absolute viscosity	—	Asphalt content Penetration Kinematic viscosity Absolute viscosity
Mix properties	Hveem stability (S-value), first and second compaction Hveem cohesiometer (C-value), first compaction only Bulk specific gravity, first and second compaction Percentage air voids, second compaction only Percentage moisture	Hveem stability (S-value), first and second compaction Hveem cohesiometer (C-value), first compaction only Bulk specific gravity, first and second compaction Percentage air voids, second compaction only Percentage moisture	Hveem stability (S-value), first and second compaction Hveem cohesiometer (C-value), first compaction only Bulk specific gravity, first and second compaction Percentage air voids, second compaction only Percentage moisture Index of retained strength	Bulk specific gravity, first and second compaction	Hveem stability (S-value), first and second compaction Bulk specific gravity, first and second compaction Percentage air voids, second compaction only

Note: 1 mm = 0.039 in.
[a]Top and bottom 77-mm lifts.

At the present time, it is difficult to determine the source of this problem, i. e., whether the basis lies in improper proportioning of materials or in an inherent feature of the recycling process used.

Figure 6. Comparison of materials specifications and average gradation of material at final belt before removal of asphalt or addition of virgin aggregate.

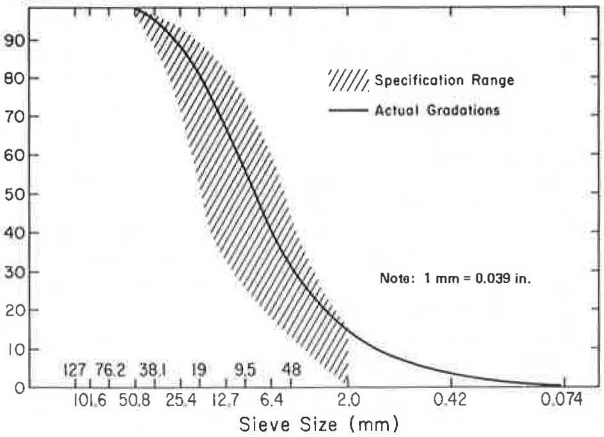
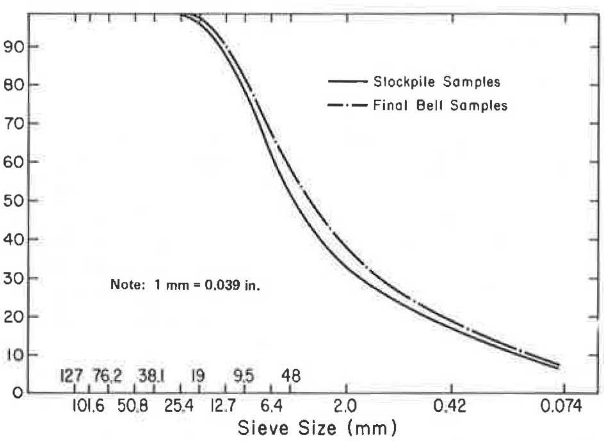


Figure 7. Average gradations of aggregate in stockpile at final belt after removal of asphalt.



Density Tests

Some problems were encountered in meeting compaction requirements, most likely because of low mixing temperatures. The highway division density specification was a minimum of 92 percent of the density achieve for the mix design specimen after second compaction. Figure 9 shows a histogram of the relative compaction achieved on cores obtained from the field based on a comparison of the density of the cores and the density of the mix design specimen at second compaction. Thirty-seven percent of the tests failed to meet the compaction specifications.

MIXING-PLANT EMISSIONS

Because of the experimental nature of this project, the Oregon Department of Environmental Quality granted a variance to allow the contractor to operate outside the present maximum opacity of 20 percent. Since several limitations were included in the variance, considerable effort was made to reduce pollutant emissions.

During the seven weeks of operation, the plant was able to consistently meet a 40 percent average opacity reading without any external control devices. Daily opacity readings followed a downward trend as modifications, experiments, and better plant control were

Figure 8. Average gradation of aggregate material at final belt after crushing and in street with addition of 20 and 30 percent virgin 19x2-mm aggregate.

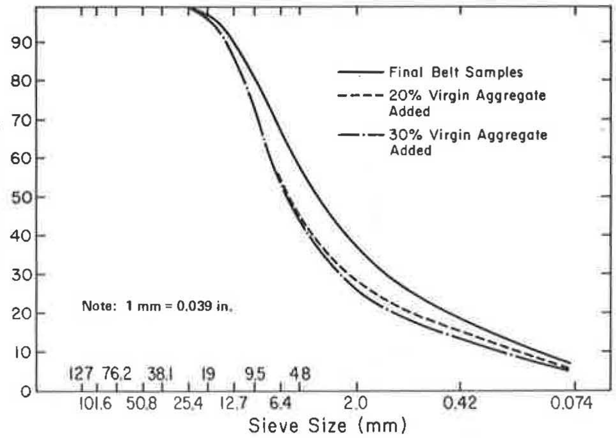


Table 4. Average values for properties of recovered asphalt and asphalt mix data at stockpile, final belt, and street.

Item	Stockpile	Final Belt	Street										
Modifications to crushed recycled asphalt													
Additional AR-2000 asphalt cement (%)	-	-	1.2	1.2	1.3	1.4	1.4	1.5	1.5	1.6	1.7	1.8	2.1
Additional 19 × 2-mm virgin aggregate (%)	-	-	10	20	20	20	30	15	20	30	20	30	30
Properties of recovered asphalt													
Penetration at 25°C (100 g, 5 s)	46	50	47	48	47	50	53	54	48	55	54	52	57
Viscosity at 60°C (Pa·s)	7712	7048	5921	4538	5854	4667	6075	4530	5060	4125	3954	4021	3680
Viscosity at 135°C (cm^2/s)	828	819	666	536	676	582	613	554	565	549	533	525	499
Asphalt content (%)	4.6	4.6	5.6	5.1	4.8	5.1	4.3	5.4	5.0	5.1	6.0	5.1	5.4
Asphalt mix data													
Bulk specific gravity													
First compaction	2.31	2.29	2.40	2.38	2.35	2.37	2.33	2.40	2.40	2.35	2.40	2.38	2.42
Second compaction	2.38	2.35	2.42	2.46	2.43	2.44	2.40	2.44	2.45	2.42	2.44	2.45	2.46
S-value													
First compaction	38	42	15	33	37	37	38	20	28	38	26	36	26
Second compaction	42	52	5	26	41	32	50	11	15	45	11	37	18
C-value	651	640	626	447	458	521	398	634	612	466	578	554	347
Air voids (%)													
First compaction	4.9	6.2	0.6	4.8	4.1	3.5	6.3	1.4	2.1	4.5	1.2	3.7	1.6
Second compaction	2.0	3.3	0.0	0.2	0.8	0.6	3.4	0.0	0.3	1.9	0.1	0.7	0.0
Moisture (%)	1.66	2.15	0.78	0.74	0.92	0.92	0.92	0.72	0.72	0.84	0.70	0.69	0.61
Index of retained wet strength (%)	-	-	85	92	84	94	73	90	86	83	91	90	87

Note: 1 mm = 0.039 in; 1 Pa.s = 10 poises; 1 cm^2/s = 100 centistokes.

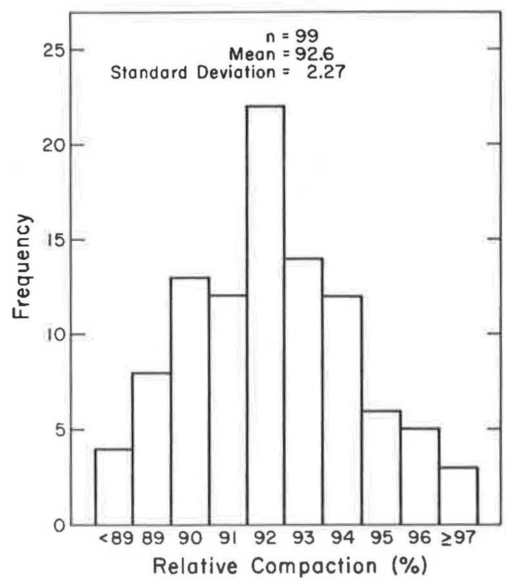
initiated. The plant was able to run 6 days with an average of less than 15 percent opacity, which is less than the maximum allowable for conventional operations.

Particulate emissions from stack testing were not to exceed 0.092 g per standard dry cubic meter (0.04 grains/ft^3) or a mass rate of 18 kg/h (40 lb/h). The plant was tested on August 23 and found to exceed the specified maximum rate of emissions by a wide margin. Test results showed a grain loading of 0.62 g/m^3 (0.269 grains/ft^3) and a mass rate of 42 kg/h (92.5 lb/h). It might have been possible to collect the large particulate by using the dust collector and water scrubber that were supplied with the plant. Unfortunately, these devices could not be used because of a shortage of water and lack of space for a settling pond.

Throughout the project, many experiments were tried in an effort to modify emission levels. The most important factors that affected the levels of emissions included mix temperature, asphalt gradation, amount of virgin aggregate and water added, plant production, and weather conditions. Emissions were reduced by

1. Keeping the mix at a cooler temperature, preferably 110°C to 116°C (230°F to 240°F);
2. Using AR-2000 asphalt instead of AR-1000 asphalt;
3. Adding 25 to 30 percent virgin 19×2-mm (0.75-in × No. 10) aggregate;
4. Adjusting the added water to account for weather conditions, especially temperature and humidity; and
5. Limiting plant production to a maximum of 236 Mg/h (260 tons/h).

Figure 9. Histogram of relative compaction achieved in Woodburn project.



COST AND ENERGY USE

In the Woodburn recycling project, 55 217 Mg (60 739 tons) of asphalt concrete mix were produced at a total cost of \$540 779.54, or \$9.80/Mg (\$8.90/ton) in place. The recycled asphalt concrete constituted approximately 40 680 Mg (44 750 tons) or 75.7 percent, the virgin aggregate constituted about 13 600 Mg (14 960.2 tons) or 24.6 percent, and the new asphalt cement added about 808 Mg (888.4 tons) or 1.46 percent. The analysis of cost and fuel use is presented for the following areas of operation: feeding and crushing the reclaimed asphalt concrete, processing and loading the recycled product, hauling to the paving site, and performing the paving operation. Table 5 gives a summary of costs and energy consumption for each of these operations.

Major savings in terms of both cost and conservation of natural resources were realized through the use of the recycled asphalt concrete. Asphalt cement was reduced to 1.46 percent by weight of the recycled mix, which resulted in a savings of 2505 Mg (2756 tons) or \$220 472.90 at the \$88/Mg (\$80/ton) bid price on this project. This assumes a 6.0 percent average asphalt content in the conventional mix.

Although no cost or energy information is available in connection with the removal and stockpiling of the old asphalt concrete, it seems reasonable that cost savings were realized over using entirely new aggregate. The unit cost of providing the virgin 19×2-mm (0.75-in × No. 10) aggregate—\$5.53/Mg (\$5.03/ton)—was substantially higher than the crushing costs for the recycled asphalt concrete—\$1.59/Mg (\$1.45/ton). In any event, important natural resources were conserved.

SUMMARY

The technological feasibility of producing recycled asphalt concrete has been demonstrated by this and other paving projects (6, 7). In this project, results of materials tests indicated that the final mixture exhibited properties similar to those of a conventional paving mixture. Early postconstruction evaluation including skid tests and ride measurements have yielded a similar conclusion. Observation, testing, and evaluation of this project will continue; it appears at this point, however, that satisfactory performance has been achieved.

CONCLUSIONS AND RECOMMENDATIONS

As a result of this project, the following conclusions can be drawn:

1. New asphalt concrete material can be successfully recycled.
2. The properties of slightly aged asphalt cement

Table 5. Costs and energy use in Woodburn recycling project.

	Cost (\$)		Energy Consumption	
Process	Total	Per Megagram	Total Fuel (L)	Liters per Megagram
Crushing recycled asphalt concrete[a]	67 776.80	1.56	30 056[b]	0.71
Processing and loading recycled product[c]	314 497.49	5.67	84 937[b]	1.55
			298 555[d]	5.46
Hauling mix to paving site[c]	86 282.89	1.56	58 222[b]	1.06
Placing mix[c]	72 222.36	1.26	9 668[b]	0.17

Note: 1 Mg = 1.1 tons; 1 L = 0.264 gal; 1 L/Mg = 0.24 gal/ton.
[a]Approximately 40 680 Mg.
[b]Diesel.
[c]Approximately 55 217 Mg of mixture (crushed asphalt concrete, virgin aggregate, new asphalt).
[d]Burner.

can be adequately modified through the addition of new "soft" asphalt cements without incorporating recycling additives.

3. Emissions in recycling are a function of many factors, including mix temperature, the grade of new asphalt added, the amount of new aggregate added, the amount of water added, plant production, and weather conditions.

4. Considerable variability in material properties can be expected. The variability in the original mix is compounded by unequal aging of the asphalt cement and further compounded by variability in the additions of new asphalt and rock.

A considerable amount of research work needs to be done in the area of recycled asphalt paving mixtures and in the design of thicknesses based on the use of these materials. At the present time, no long-term information on the in-service performance of these paving materials is available. More work needs to be done to evaluate fundamental material properties and their correlation with (a) types and amounts of softening agents, (b) types and gradations of additional aggregate, and (c) types of mixing techniques. As more of the problems are solved, recycling can become a workable construction alternative to meet changing requirements in the supply of materials.

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REFERENCES

1. Work Plan for Recycling Asphalt Pavements: FHWA Demonstration Project No. 39. Federal Highway Administration, U.S. Department of Transportation, Negotiated Contract DOT-FH-12-220, Exhibit A, 1976.
2. Laboratory Manual of Test Procedures. Materials and Research Section, Highway Division, Oregon Department of Transportation, Salem.
3. J. Dumler and G. Beecroft; Oregon Department of Transportation. Recycling of Asphalt Concrete: Oregon's First Hot Mix Project. Demonstration Projects Division, Federal Highway Administration, U.S. Department of Transportation, Interim Rept., Nov. 1977.
4. R.W. Smith. A Summer of Recycling: An Update on Asphalt Pavement Recycling. Paving Forum, Winter 1978.
5. W.G. Whitcomb. An Evaluation of Oregon's First Asphalt Recycling Project: Woodburn, Oregon, Summer 1977. Department of Civil Engineering, Oregon State Univ., Corvallis, draft rept., April 1978.
6. P. Bolander and B. Stein; Oregon State University. An Evaluation of the Blewett Pass Recycling Project. Federal Highway Administration, U.S. Department of Transportation, Interim Rept., Feb. 1978.
7. J.A. McGee and A.J. Judd. Recycling of Asphalt Concrete: Arizona's First Project. Arizona Department of Transportation, Phoenix, Jan. 1978.

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Effect of Portland Cement on Certain Characteristics of Asphalt-Emulsion-Treated Mixtures

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Findings are reported of a detailed laboratory investigation to evaluate the use of portland cement (1 percent of weight of dry aggregate) as an additive to asphalt-emulsion-treated mixtures (AETMs) and to study the effect of the interaction of portland cement with aggregate gradation and asphalt emulsion content on the design parameters and properties of AETMs by use of Marshall equipment. The evaluation was conducted at different curing stages of the mix. One type of aggregate (sand and gravel) and one type and grade of asphalt emulsion were used in the study. A modified Marshall method was used for preparing and testing the specimens. The evaluation of AETM properties produced a number of significant results. The use of portland cement as an additive to the AETM proved to be beneficial in improving its properties. This result must be viewed with caution, however, since it was found that the effect of portland cement on AETM performance was significantly influenced by aggregate gradation, asphalt emulsion content, added moisture content, and curing