EVALUATION OF OREGON'S FIRST HOT MIX ASPHALT RECYCLING PROJECT -- WOODBURN, OREGON, 1977

by

William G. Whitcomb
Research Assistant
Department of Civil Engineering
Oregon State University

Gordon Beecroft
Research Engineer
Oregon State Department of Transportation

and

James E. Wilson
Materials Engineer
Oregon State Department of Transportation

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ABSTRACT

Pavement recycling has been suggested as a viable alternative to more conventional methods of pavement rehabilitation as a means of offsetting some of the problems resulting from spiraling energy costs and shortages of raw materials. This paper presents a discussion of the Woodburn Asphalt Recycling Paving Project, Oregon's first experience at large-scale asphalt concrete recycling utilizing a hot-mix process. The project is described briefly and overlay and mix designs are indicated. The construction program and specific equipment utilized are reviewed. The program of material sampling and testing and data collection is described. Test results are summarized. Special emphasis is given to an investigation of possible changes in material properties through the construction process. A summary of those factors most affecting emission production is presented. Costs and fuel consumption are summarized and possible savings over a similar conventional paving project are highlighted. Specific recommendations are presented to other agencies proposing similar projects. Finally, future research needs are outlined.

INTRODUCTION

The need to reduce fuel consumption and conserve natural resources has been an item of ever-increasing importance during recent years. In 1976, the Oregon State Highway Division was faced with the problem of disposing of nearly 444,820 kN (50,000 tons) of asphalt concrete pavement placed for temporary purposes in the rehabilitation of Interstate-5 (I-5) between Salem, Oregon and Woodburn, Oregon. Officials of the Highway Division recognized the possibility of utilizing this asphalt concrete as raw material for recycling and, with the assistance of federal funding through Region 15 of FHWA, a demonstration project was initiated and became known as the Woodburn Asphalt Pavement Recycling Project.

In order to fulfill the objectives of the National Demonstration Project Program for Asphalt Pavement Recycling, a comprehensive work plan was developed, specifying 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 in fulfilling its responsibilities through the first year of project evaluation. Specifically, the objectives of this paper are:

(1) To present a description of the project, including its location, overlay thickness design, asphalt concrete mix design and the final mix specifications.

(2) To indicate the final construction procedure and equipment utilized.

(3) To describe the program of materials sampling and testing and data collection of information on weather, emissions, costs and energy usage.

(4) To present the material test results and highlight any changes in material properties through the construction process.

(5) To document the levels of emissions reported through the project and indicate factors that seemed to affect the increase or decrease of opacity and particulates.

(6) To present a summary of the costs and energy consumption of this project and indicate possible savings compared to a conventional asphalt concrete paving project.

(7) To present recommendations to other agencies proposing similar projects and the conclusions resulting from this project.

PROJECT DESCRIPTION

Location

The Woodburn Recycling Project consisted of widening and overlaying a 16 km (10 mile) section between Woodburn and St. Paul of 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 in order to determine the characteristics of the pavement to be overlaid. The existing highway prior to reconstruction had an asphalt concrete surface 6.1 m to 7.3 m (20 to 24 feet) in width. A sample of eight cores was obtained. Test results from those cored indicated a surface wearing course thickness ranging from 76 to 127 mm (3 to 5 inches) and a base course thickness ranging from 0 to 178 mm (0 to 7 inches). Average values for surface and base course thicknesses were 114 and 127 mm (4½ and 5 inches), respectively, as shown in Figure 1a.

In February of 1977, A Benkelman Beam inventory was conducted, both to develop an overlay thickness design and document any deflection changes resulting 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 foot) study section are recorded in Table 1.

As a result of these investigations, a 152 mm (6 inch) overlay design was developed. Two 3.7 m (12 foot) travel lanes were provided together with paved shoulders between 305 mm and 610 mm (1 and 2 feet) wide, yielding an overall pavement width of 7.9 m to 8.5 m (26 to 28 feet). The overlay was to be placed over the entire pavement width in two 76 mm (3 inch) lifts. This post-construction cross-section is illustrated in Figure 1b (1).

Preliminary Specifications

The specific job mix formula originally used in producing the now-recycled material consisted of the following gradations:

Sieve Size (mm)	Percent Passing by Total Weight of Mix
19 - 6	34.8%
6 - 2	28.7%
2 - 0	30.9%
Asphalt Cement	5.6%
	100.0%

The asphalt content was later changed to 6.0% 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 which would be likely to achieve a desirable mixture. Based on the experience of past recycling projects, the following proportions, with their corresponding tolerances, were specified:

Component	Percent By Total Weight of Mix	Tolerance
Crushed Asphalt Concrete	78 - 100	± 4%
Additional 19 mm x 2 mm Aggregate	0 - 20	± 4%
Additional Asphalt Cement	0 - 2	± 0.5%

Additionally, gradation specifications for both the crushed asphalt concrete and the virgin aggregate were developed, and are shown in Table 2.

The 50 mm (2 inch) maximum size indicated for the crushed asphalt concrete was specified to achieve thorough heating of all of the particles. The 19 mm (3/4 inch) and 2 mm (#10) gradations for the crushed asphalt concrete were specified to minimize the possibility of fracturing the aggregate in the old asphalt concrete and thus minimizing the production of new fines.

The gradations for the virgin aggregate were specified to insure that there would be a sufficient percentage of voids in the resulting mix.

Mix Design

The final specifications required the contractor to provide representative samples of crushed material fifteen days prior to producing any mixture for use. The Oregon State Highway Division's Materials Section undertook a mix design study on these samples, utilizing the Oregon Mix Design Procedure (modified Hveem method) (2) to determine the proper amounts of asphalt and 19 mm x 2 mm (3/4" x #10) virgin aggregate which should be added to the crushed material to achieve the Division's design criteria, as shown in Table 3. At times, all criteria could not be met and engineering judgement was used in determining the recommendations. The recommended asphalt additions and corresponding mix properties for mixes containing 100%, 90% and 80% recycled asphalt concrete are shown in Table 4.

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 included in the design criteria, penetration and viscosity tests were run on the recovered asphalt before and after the addition of different grades and percentages of asphalt cement. However, few tests were conducted and the results were inconclusive.

Field Variation of Job Mix Proportions

There were several significant deviations from the aforementioned recommendations once actual construction began. Figure 2 indicates the amounts of new asphalt and virgin aggregate recommended by the mix designs for surface and base courses, and is represented by the solid lines. The dotted lines represent extrapolations of the mix design to include a 30% virgin aggregate addition. The solid dots shown represent actual mix proportions used during construction operations. All of the proportions include more asphalt than originally recommended, and the 30% aggregate addition, while not laboratory tested, was used extensively in the field.

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

The possibility that the crushed asphalt concrete sample 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% recycled mix was 5.6%. The average asphalt content of the crushed asphalt concrete samples obtained during construction was only 4.6%. The range of final asphalt contents after the addition of new asphalt cement in the mix design was 5.1% to 5.6% for the base course. Even though more new asphalt was added in field mixing operations, the final average asphalt content was 5.4% for 23 samples of the top lift and 5.8% for 23 samples of the bottom lift. This is very close to that obtained in the mix design following the addition of new asphalt cement.

In addition to the combinations used during construction (Figure 2), a combination of 1.5% Shell AR-1000 together with 20% 19 mm x 2 mm (3/4" x #10) aggregate was tried. Also, 30% 6 mm x 2 mm (1/4" x #10) aggregate was used with 2.1% AR-2000 asphalt. The use of these materials was discontinued for the following reasons:

(1) The mix incorporating AR-1000 yielded unacceptable emission levels, and

(2) The use of 6 mm x 2 mm (1/4" x #10) aggregate did not improve performance over the 19 mm x 2 mm (3/4" x #10) aggregate and was more costly.

Consequently, except for these experiments, AR-2000 asphalt cement and 19 mm x 2 mm (3/4" x #10) aggregate were used throughout the project.

CONSTRUCTION PROCEDURES AND EQUIPMENT UTILIZED

The final construction procedure utilized in mixing and placing the recycled asphalt concrete was as follows. The stockpiled old asphalt concrete was first crushed to the desired aggregate specification, utilizing equipment arranged in the configuration shown in Figure 3. This configuration was considered desirable following a comprehensive series of experiments in the laboratory, in a commercial crushing plant and on-site prior to the initiation of paving operations. The material was fed into the crusher using one D-8H crawler tractor equipped with rippers. An additional D-6 crawler tractor was used intermittently through the job, usually operating a total of two hours per day.

The crushed asphalt concrete was then stockpiled. In order 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 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 weighing new aggregate and one weighing the crushed asphalt concrete-virgin aggregate blend.

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 the water could be added in known percentages.

A dryer drum plant manufactured by Boeing Construction Company with a 3560 kN per hour (400 TPH) capacity was used to heat and mix the recycled asphalt - aggregate blend with new asphalt. The plant was modified 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 inch) diameter holes, was placed between the burner and the drum entrance to allow heat transfer while simultaneously providing a barrier between the flame and the recycled material. Additionally, a high-speed conveyor was used to feed the cold material into the drum in order to "throw" the material further from the heat. Dust control was aided through the use of a steel baffle 4.3 m (14 feet) from the rear of the drum, covering all but 254 mm (10 inches) around the perimeter of the inside drum diameter (3,4).

The mix was hauled to the paving site using twenty cubic yard 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 using a 107 kN (12 ton) Bomag 220-A vibrator roller. A Buffalo three-leg steel wheel roller weighing 117 kN (13 tons) was used for intermediate rolling, while finish rolling was accomplished with an 89 kN (10 ton) Ray-Go vibrator roller, rolling only static.

MATERIAL SAMPLING AND TESTING AND INFORMATION GATHERING PROGRAM

Materials Sampling and Testing

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 illustrated in Figure 4.

Pavement cores were also obtained and tested following completion of paving operations. The battery of tests performed on each of the sample types is presented in Table 5.

Information Gathering Program

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

MATERIAL TEST RESULTS

Gradations

The gradation of the crushed asphalt concrete prior to asphalt removal is shown in Figure 5. The shaded area represents the gradation specifications for this material. No problem was found meeting the specifications, except for material passing the 2mm (#10) screen. This specification was exceeded in 58% of the samples tested, but in those samples, the amount passing the 2 mm (#10) sieve never exceeded 18%.

The average gradations of the aggregate materials in the recycled asphalt concrete before and after crushing can be compared through inspection of Figure 6. The aggregate in the recycled asphalt concrete is finer after crushing, indicating that both aggregate particles and asphalt-aggregate chunks were fractured. It is uncertain at this point whether this fracturing was due to the crushing process or to the action of the equipment working on the stockpile.

The agerage gradations of the aggregate material at the final belt and at the street following additions of 20% and 30% 19 mm x 2 mm (3/4" x #10) virgin aggregate are shown in Figure 7. Visual inspection of the figure indicates that there is little difference in the aggregate gradations following the addition of 20% or 30% 19 mm x 2 mm (3/4" x #10) virgin aggregate. The material with 20% additional virgin aggregate is finer in the sizes 6 mm - 0 (1/4" - 0).

Both blends are significantly coarser than the aggregate material at the final belt. Again, this would be expected due to the addition of the 19 mm x 2 mm (3/4" x #10) aggregate. Note, however, that the percent passing the 0.074 mm (#200) sieve does not differ significantly, although it is slightly higher for the final belt material than for the blends.

Recovered Asphalt Properties

Average values for recovered asphalt properties in samples taken in the stockpile and at the crusher's final belt are shown in Table 6. Table 6 also illustrates the average recovered asphalt properties for eleven combinations of asphalt and virgin aggregate added to the recycled asphalt concrete. Again, as expected, higher asphalt additions led to lower viscosities and higher penetrations in the recycled asphalt concrete mixture. Note also that the crushing operation did not seem to affect the recovered asphalt properties at all.

Asphalt Mix Properties

Table 6 also lists 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 regarding the effect of the various construction processes on the mix properties.

Statistically, there is a significant difference ($\alpha = 1\%$) in the means for samples obtained at the stockpile before crushing and at the final belt after crushing for the following tests (5):

(1) Bulk Specific Gravity (First and Second Compaction),

(2) Hveem Stabilometer (Second Compaction), and

(3) Percent Air Voids.

Since recovered asphalt properties 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 show a significant number of combinations of asphalt and virgin aggregate which 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

At the present time, it is difficult to conclude 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.

Density Tests

Some problems in meeting compaction requirements were encountered, most likely due to low mixing temperatures. The Highway Division density specification was a minimum of 92% of the density achieved for the mix design specimen after second compaction. Figure 8 illustrates a histogram of the relative compaction achieved on cores obtained from the field. Thirty-seven percent of the tests failed to meet the compaction specifications.

MIXING PLANT EMISSIONS

Due to 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%. Several limitations were included in the variance and hence, there was considerable effort put forth to reduce emissions.

During the seven weeks of operation, the plant was able to meet a 40% average opacity reading consistently without any external control devices. Daily opacity readings followed a downward trend as modifications and experiments and better plant control were initiated. The plant was able to run six days with an average of less than 15% opacity, which is less than the maximum allowable for conventional operations.

Particulate emissions from stack testing were not to exceed 0.0009 Newtons per standard dry cubic meter (0.04 grains per cubic foot) or a mass rate of 178 Newtons (40 pounds) per hour. The plant was tested on August 23 and found to exceed the specified maximum loading by a wide margin. Test results showed a grain loading of 0.0060 Newtons per standard cubic meter (0.269 grains per cubic foot) and a mass rate of 411 Newtons (92.5 pounds) per hour. Collection of the large particulate may have been possible with the dust collector and water scrubber that was supplied with the plant. Unfortunately, the use of these devices was impractical due to the shortage of water and lack of space for a settling pond.

Factors Affecting Emissions

Through the duration of the project, many experiments were tried with respect to modifying emission levels. The most important factors affecting emission levels included mix temperature, asphalt grade, amount of virgin aggregate and water added, plant production and weather conditions. Emissions were reduced under the following conditions:

(1) Keeping the mix at cooler temperature, preferably 110^{o} to 116^{o} C (230^{o} to 240^{o} F).

(2) Using AR-2000 asphalt instead of AR-1000 asphalt.

(3) Adding 25 to 30% virgin 19 mm x 2 mm (3/4" x #10) aggregate.

(4) Adjusting the added water to account for weather conditions, especially temperature and humidity.

(5) Limiting plant production to a maximum of 2313 kNPH (260 TPH).

COST AND ENERGY USAGE

In the Woodburn Recycling Project, 540,358 kN (60,739 tons) of asphalt concrete mix were produced at a total cost of $540,779.54 at $1.00 per kN ($8.90 per ton), in place. The recycled asphalt concrete comprised 398,114 kN (44,750 tons) or 75.7%, the virgin aggregate comprised 133,092 kN 14,960.2 tons) or 24.6%, and the new asphalt cement added 7904 kN (888.4 tons) or 1.46%. The cost and fuel usage analysis is presented in the following work units: feeding and crushing the reclaimed asphalt concrete, processing and loading the recycled product, hauling to the paving site and performing the paving operation. Table 7 presents the summary of costs and energy usage in each of these work units.

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% by weight of the recycled mix, resulting in a savings of 24,518 kN (2,756 tons) or $220,472.90 at the $9 per kN ($80 per ton) bid price on this project. This assumes a 6.0% average asphalt content in the conventional mix.

While no cost or energy information is available regarding removing and stockpiling the old asphalt concrete, it seems reasonable that cost savings were realized over using entirely new aggregate. The unit cost in providing the virgin 19 mm x 2 mm (3/4" x #10) aggregate, $0.90 per kN ($5.03 per ton), was substantially higher than the crushing costs for the recycled asphalt concrete, $0.16 per kN ($1.45 per ton). In any event, important natural resources were conserved.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

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

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

(4) A high amount of variability in material properties can be expected. The variability in the original mix is compounded by unequal aging of the asphalt cement and then further compounded by the variability in the additions of new asphalt and rock.

Recommendations for Further Research

A considerable amount of research work needs to be done in the area of recycled asphalt paving mixtures and in thickness design based on the use of these materials. At the present time, no long-term information is available regarding the performance of these paving materials in service. More work needs to be done to evaluate fundamental material properties and their correlation with the following:

(1) Types and amounts of softening agents,

(2) Types and gradations of additional aggregate, and

(3) Types of mixing techniques.

As more of the problems are solved, recycling can become a viable construction alternative to meet the changing materials supply requirement.

SUMMARY

The technological feasibility of producing recycled asphalt concrete has been demonstrated by this and other paving projects (6,7). In this project, material test results indicate that the final mixture exhibits properties similar to a conventional paving mixture. Early post-construction evaluation including skid tests and ride measurements have yielded a similar conclusion. Observation, testing and evaluation of this particular project will continue; however, it appears at this point that satisfactory performance has been obtained.

ACKNOWLEDGEMENTS

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LIST OF TABLES

TABLE 1

Pavement Deflection Measurements: St. Paul - Woodburn Asphalt Pavement Recycling Project

Section Location		Traffic Lane	Deflection Data Summary (mm) [a]		
Beginning Station	Ending Station		Mean	Std. Deviation	Std. Dev. / Mean [b]
89+00	96+50	Eastbound	1.09	0.25	0.23
115+50	123+00	Westbound	1.02	0.36	0.35
132+00	139+50	Eastbound	0.97	0.23	0.24
166+50	174+00	Westbound	1.14	0.30	0.27
192+00	199+50	Eastbound	0.69	0.23	0.33
220+50	228+00	Westbound	0.97	0.18	0.18
253+00	260+50	Eastbound	1.37	0.58	0.43
271+50	279+00	Westbound	1.09	0.43	0.40
288+00	295+50	Eastbound	1.12	0.330	0.30
318+50	326+00	Westbound	1.19	0.46	0.38
358+00	365+50	Eastbound	1.22	0.30	0.25
371+50	379+00	Westbound	1.27	0.76	0.60
409+00	416+50	Eastbound	1.19	0.53	0.45
429+50	437+00	Westbound	0.97	0.23	0.24
474+00	481+50	Eastbound	1.19	0.28	0.24
481+50	489+00	Westbound	1.30	0.45	0.34

[a] Adjusted to pavement temperature of 70°F

[b] The Standard Deviation / Mean is termed the Coefficient of Variation

Note: 1 inch = 25.4 mm

TABLE 2

Gradation Specifications for Crushed Asphalt Concrete and Virgin 19 mm x 2 mm Aggregate

(a) Crushed Asphalt Concrete

Sieve Size (mm)	Percent Passing by Weight
51	100
19	50 - 90
2	0 - 15

(b) Virgin Aggregate

Sieve Size (mm)	Percent Passing by Weight
25.4	100
10	95 - 100
6	25 - 50
2	0 - 19
0.074	0 - 4

Note: 1 inch = 25.4 mm

TABLE 3

Oregon Mix Design Criteria

PROPERTY	SURFACE	BASE	SHOULDER
Stability - "S" Value			
1st Compaction	30 minimum	30 minimum	30 minimum
2nd Compaction	30 minimum	--	--
Air Voids	About 4%	About 2%	About 2%
Retained Wet Strength	70% minimum	70% minimum	70% minimum
Film Thickness	Sufficient	Sufficient	Sufficient

TABLE 4. Summary of Mix Properties at Recommended New Asphalt Additions

ASPHALT CONTENT AND ADDITION	100% Recycled Asphalt Concrete		90% Recycled Asphalt Concrete 10% 19 mm x 2 mm Virgin Aggregate		80% Recycled Asphalt Concrete 20% 19 mm x 2 mm Virgin Aggregate	
	SURFACE	BASE	SURFACE	BASE	SURFACE	BASE
Asphalt Content in Crushed Recycled Pavement (%)[a]	5.6	5.6	5.0[b]	5.0[b]	4.5[b]	4.5[b]
Recommended Asphalt Addition (%)	0.0	0.3	0.3	0.5	0.6	0.8
Final Asphalt Content (%)	5.6	5.9	5.3	5.5	5.1	5.3

MIX PROPERTIES	100% Recycled Asphalt Concrete		90% Recycled Asphalt Concrete 10% 19 mm x 2 mm Virgin Aggregate		80% Recycled Asphalt Concrete 20% 19 mm x 2 mm Virgin Aggregate	
	SURFACE	BASE	SURFACE	BASE	SURFACE	BASE
Stabilometer Value - "S"						
1st Compaction	30.0	27.0	33.2	32.0	32.6	31.8
2nd Compaction	36.0	19.8	36.2	27.0	35.6	34.8
Air Voids (%)						
1st Compaction	5.7	4.7	4.3	3.7	4.9	4.3
2nd Compaction	2.8	1.8	2.6	2.0	2.8	2.0
Bulk Specific Gravity						
1st Compaction	2.32	2.33	2.35	2.36	2.35	2.36
2nd Compaction	2.39	2.40	2.39	2.40	2.41	2.42
Cohesiometer Value - "C"						
1st Compaction	572	648	863	878	485	471

[a] Percent by total weight of mix

[b] These values are obtained as follows: (Asphalt Content in 100% Recycled Asphalt Concrete) x (Percentage of Recycled Asphalt Concrete in Mix)

Note: 1 inch = 25.4 mm

TABLE 5. Tests Performed on Each of Several Sample Types During and After Construction

TEST TYPE	SAMPLE TYPES				
	DURING CONSTRUCTION				AFTER CONSTRUCTION
	Recycled Asphalt Concrete (from Stock-pile before Crushing)	Recycled Asphalt Concrete (from Final Belt Following Crushing)	Box Samples	Compaction Cores	Pavement Cores (Top and Bottom Three-inch Lifts)
Tests for Aggregate Properties	Gradations before and after asphalt removal	Gradations before and after asphalt removal	Gradations following asphalt removal	---	Gradations following asphalt removal
Tests for Recovered Asphalt Properties	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
Tests for Mix Properties	Hveem Stability ("S"-value), 1st and 2nd Compaction Hveem Cohesiometer ("C"-value), 1st Compaction Only Bulk Specific Gravity 1st and 2nd Compaction Percent Air Voids 2nd Compaction Only Percent Moisture	Hveem Stability ("S"-value), 1st and 2nd Compaction Hveem Cohesiometer ("C"-value), 1st Compaction Only Bulk Specific Gravity 1st and 2nd Compaction Percent Air Voids 2nd Compaction Only Percent Moisture	Hveem Stability ("S"-value), 1st and 2nd Compaction Hveem Cohesiometer ("C"-value), 1st Compaction Only Bulk Specific Gravity 1st and 2nd Compaction Percent Air Voids 2nd Compaction Only Percent Moisture Index of Retained Strength	Bulk Specific Gravity 1st and 2nd Compaction	Hveem Stability ("S"-value), 1st and 2nd Compaction Bulk Specific Gravity 1st and 2nd Compaction Percent Air Voids 2nd Compaction Only

TABLE 6. Summary of Average Values for Recovered Asphalt Properties and Asphalt Mix Data at the Stockpile, Final Belt and Street

MODIFICATIONS TO CRUSHED RECYCLED ASPHALT	STOCKPILE SAMPLES	FINAL BELT SAMPLES	STREET SAMPLES										
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 mm x 2 mm Virgin Aggregate (%)	-	-	10	20	20	20	30	15	20	30	20	30	30

RECOVERED ASPHALT PROPERTIES	STOCKPILE SAMPLES	FINAL BELT SAMPLES	STREET SAMPLES										
Penetration at 25° C (dmm)	46	50	47	48	47	50	53	54	48	55	54	52	57
Viscosity at 60° C (poises)	7712	7048	5921	4538	5854	4667	6075	4530	5060	4125	3954	4021	3680
Viscosity at 135° C (centistokes)	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	STOCKPILE SAMPLES	FINAL BELT SAMPLES	STREET SAMPLES										
Bulk Specific Gravity													
1st 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
2nd 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
Stabilometer Value - "S"													
1st Compaction	38	42	15	33	37	37	38	20	28	38	26	36	26
2nd Compaction	42	52	5	26	41	32	50	11	15	45	11	37	18
Cohesiometer Value - "C"	651	640	626	447	458	521	398	634	612	466	578	554	347
Air Voids (%)													
1st 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
2nd 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

TABLE 7

Summary of Costs and Energy Usage in the Woodburn Recycling Project

PROCESS	COST	ENERGY CONSUMPTION
Crushing the Recycled Asphalt Concrete	$ 67,776.80 ($0.16/kN)[a]	Diesel Fuel: 30,056 liters (0.072 liters/kN)[a]
Process and Load the Recycled Product	$314,497.49 ($0.58/kN)[b]	Diesel Fuel: 84,937 liters (0.157 liters/kN)[b] Burner Fuel: 298,555 liters (0.553 liters/kN)[b]
Hauling the Mix to the Paving Site	$ 86,282.89 ($0.16/kN)[b]	Diesel Fuel: 58,222 liters (0.108 liters/kN)[b]
Placing the Mix	$ 72,222.36 ($0.13 kN)[b]	Diesel Fuel: 9,668 liters (0.018 liters/kN)[b]

[a] 414,714 kN of crushed recycled asphalt concrete

[b] 540,350 kN of the asphalt concrete mixture (crushed ac, virgin aggregate, new asphalt)

Note: 1 ton = 8.8964 kN

1 gallon = 3.785 liters

LIST OF FIGURES

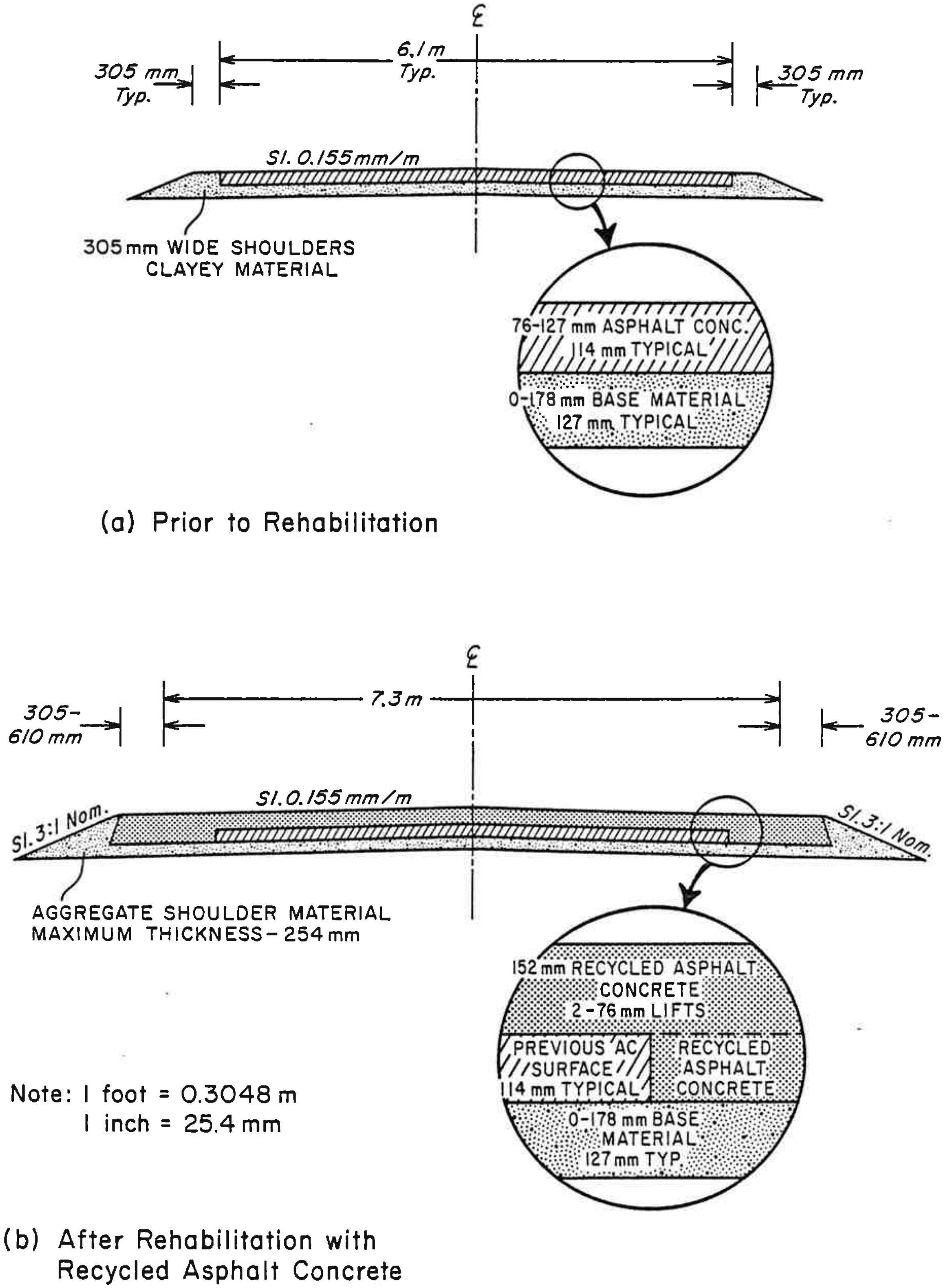


FIGURE 1. St. Paul - Woodburn Section of the Hillsboro - Silverton Highway: Typical Roadway Sections

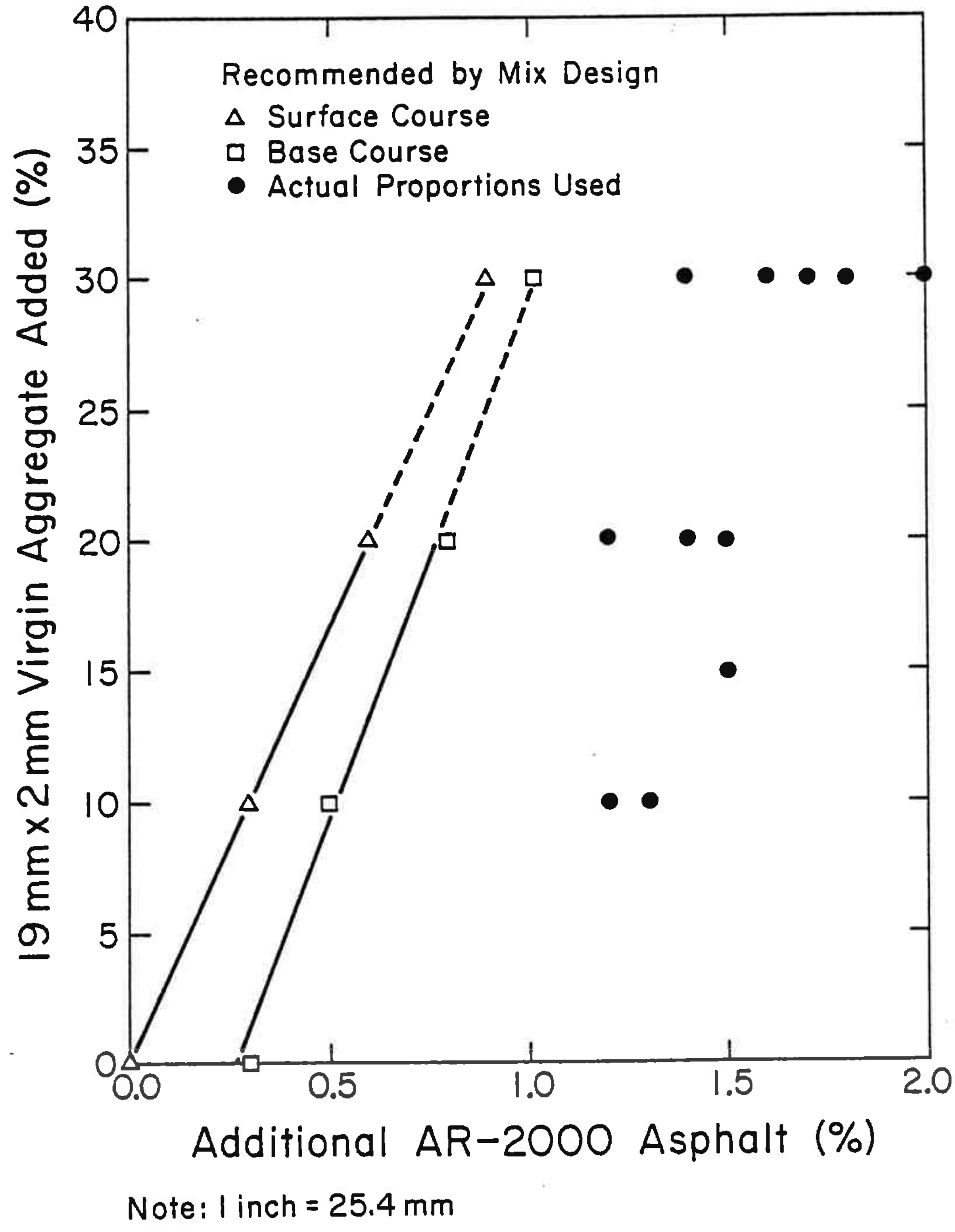


FIGURE 2. Asphalt Additions Recommended by Mix Design and Asphalt Additions Actually Used

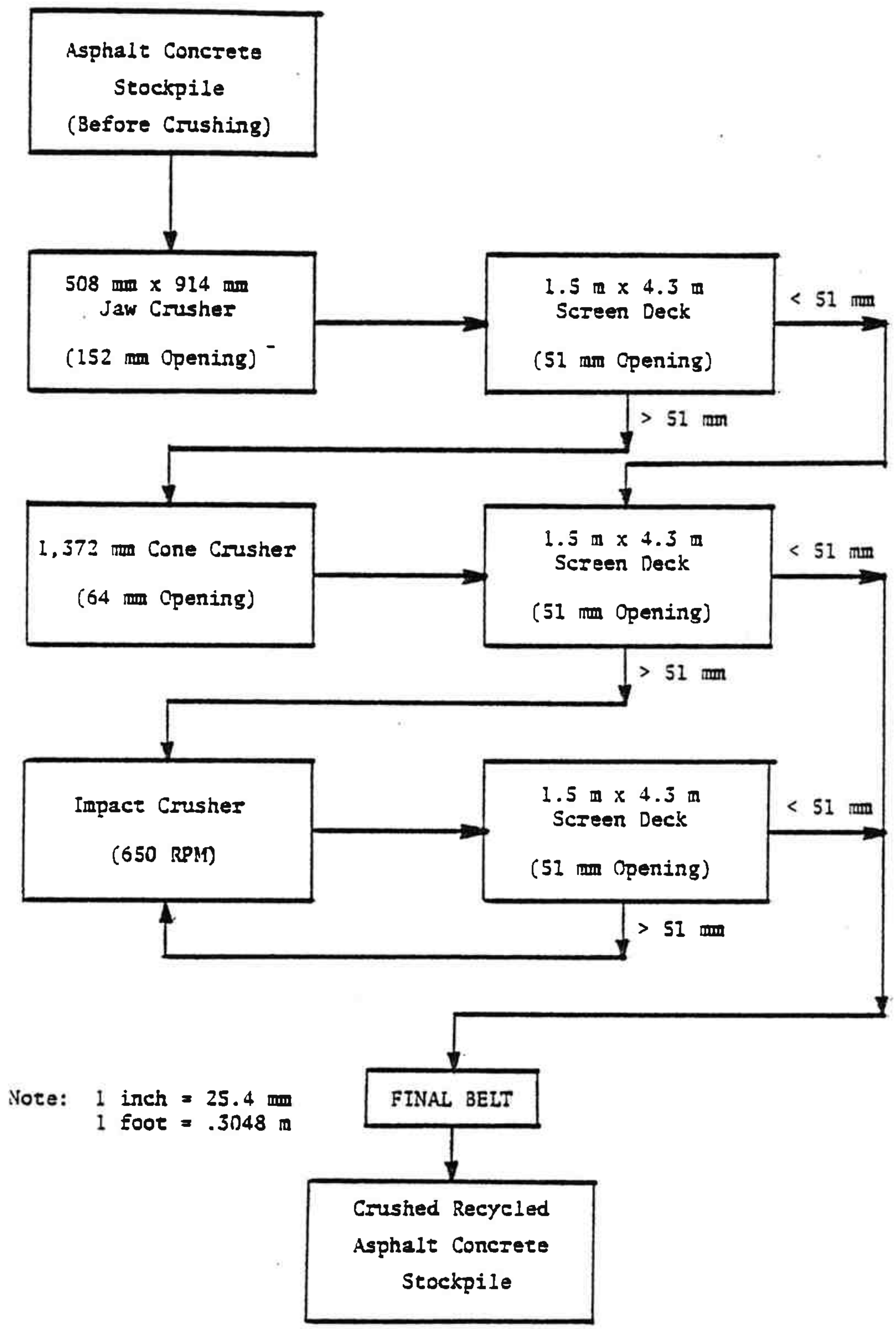


FIGURE 3. Final Crushing Configuration

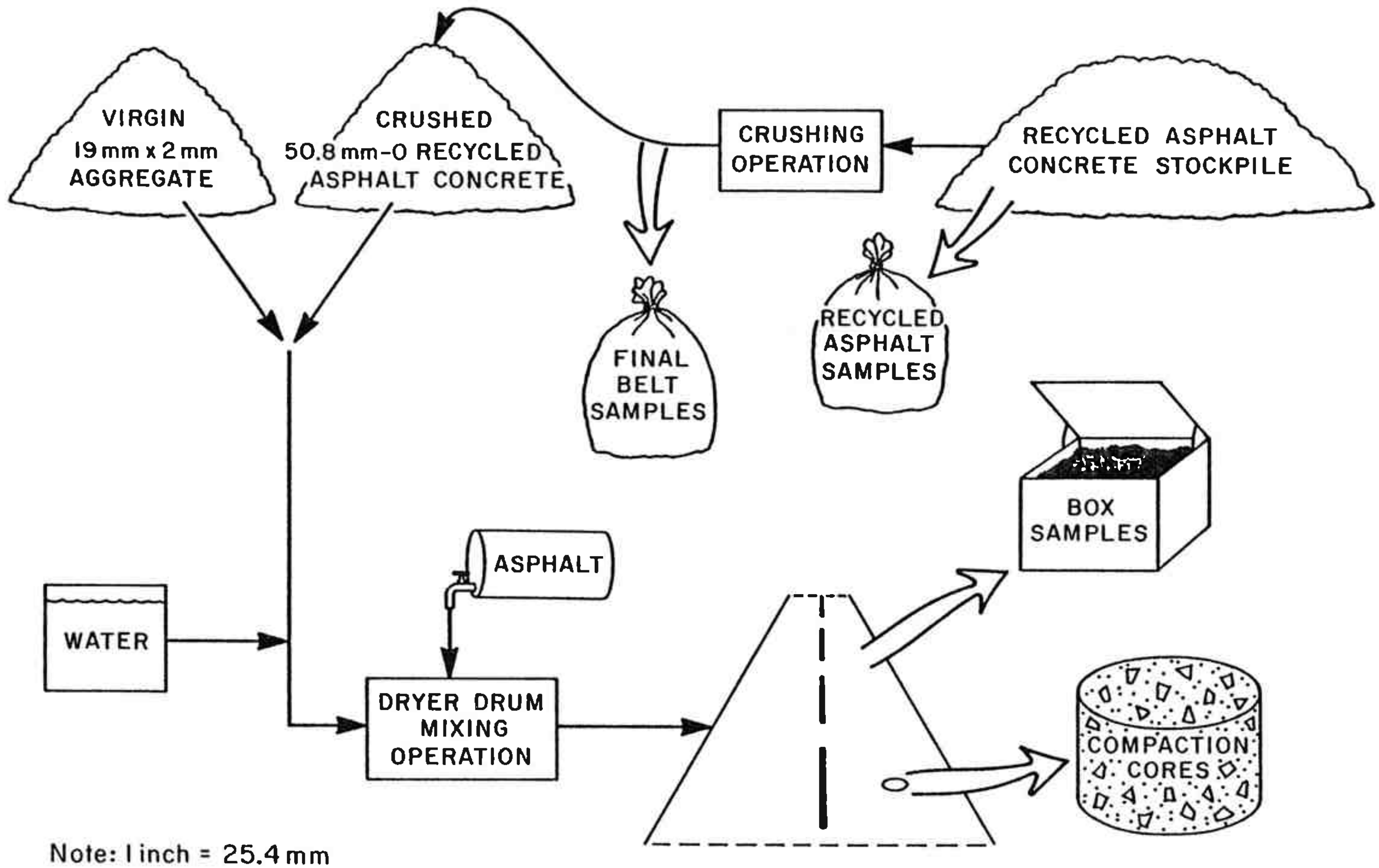


FIGURE 4. Location of Sampling Sites in the Woodburn Construction Operation

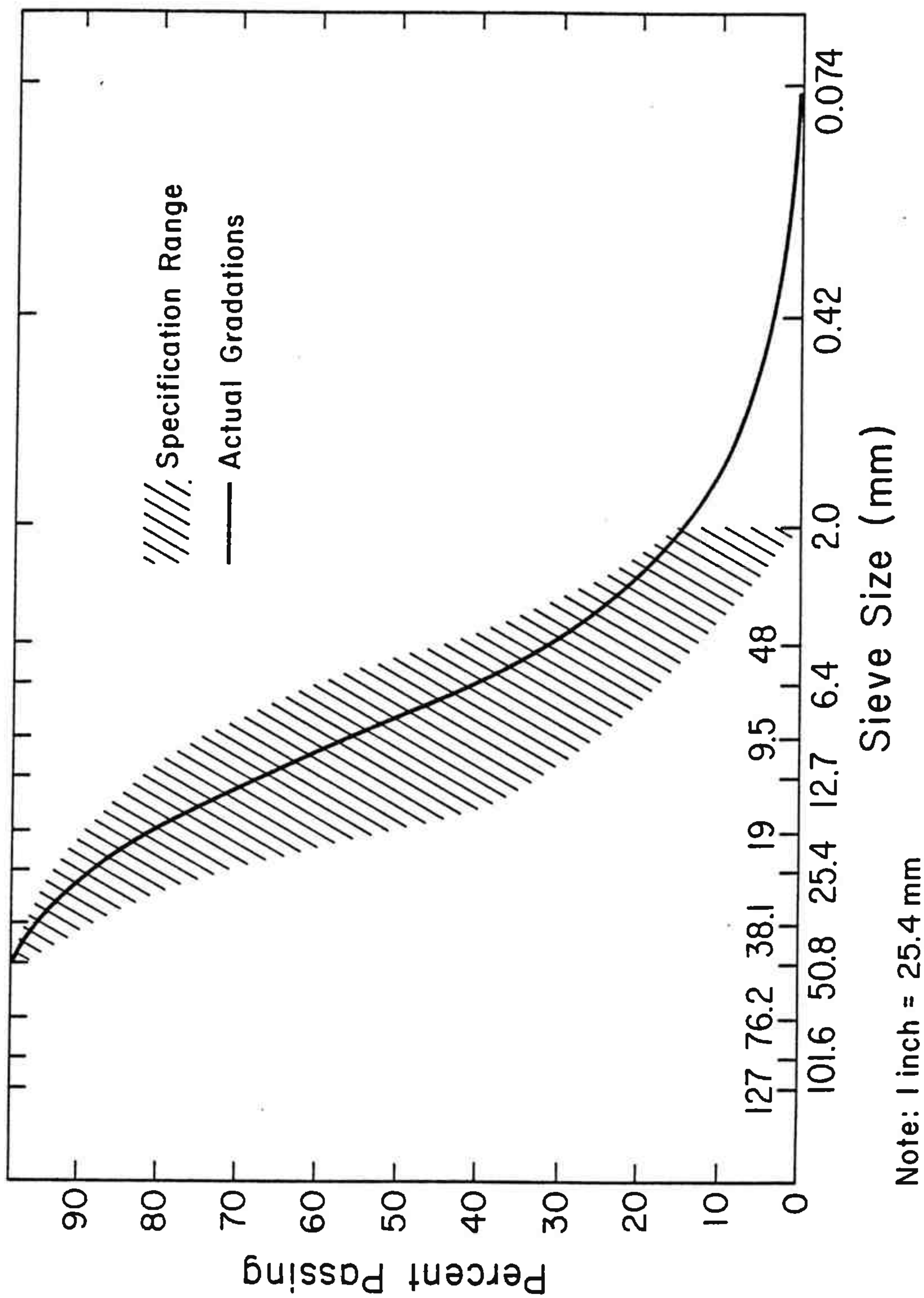
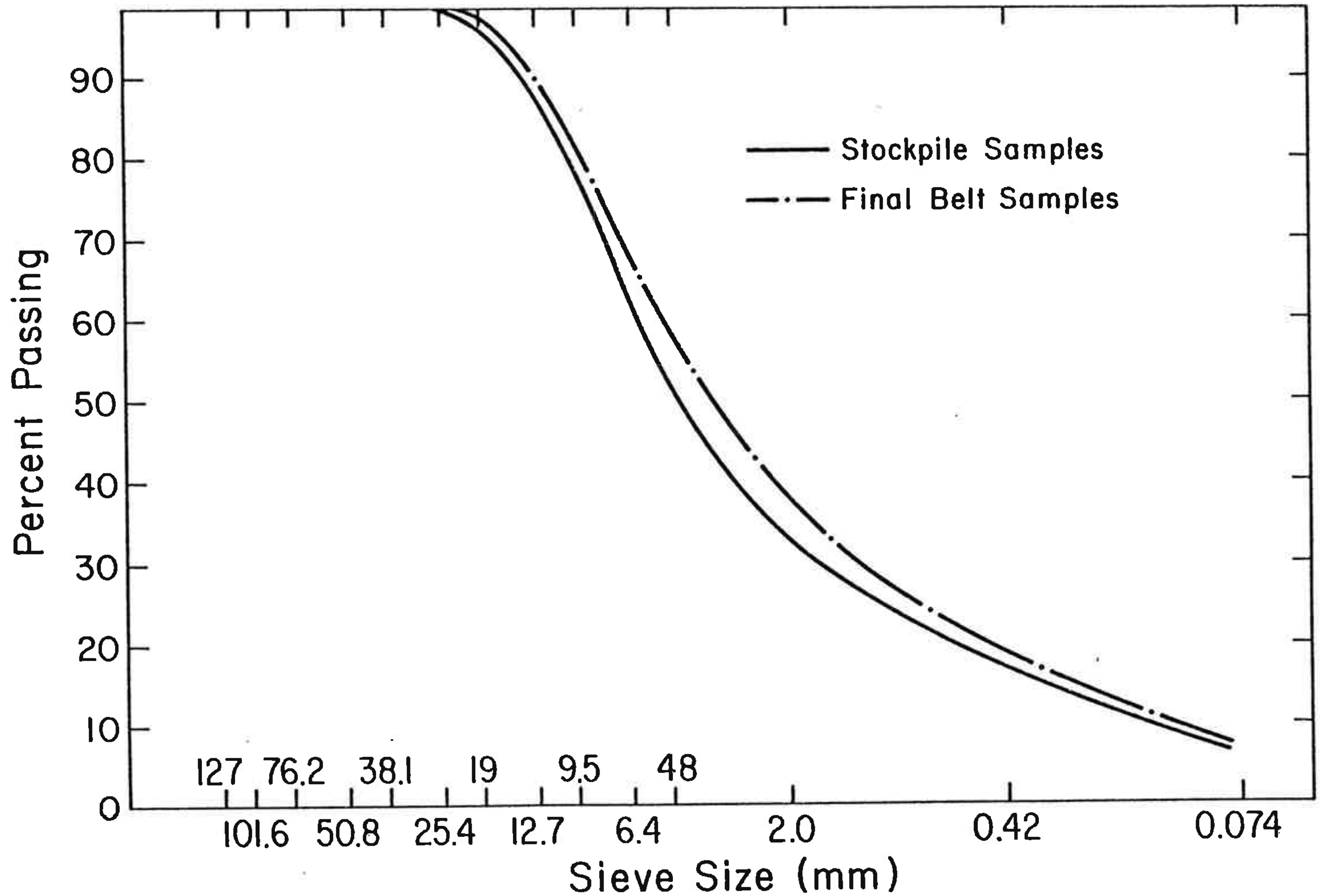


FIGURE 5. Average Gradation of Material at the Final Belt Prior to Asphalt Removal or Addition of Virgin Aggregate Compared to the Material Specifications



Note: I inch = 25.4 mm

FIGURE 6. Average Gradations of Aggregate in the Stockpile and at the Final Belt Following Asphalt Removal

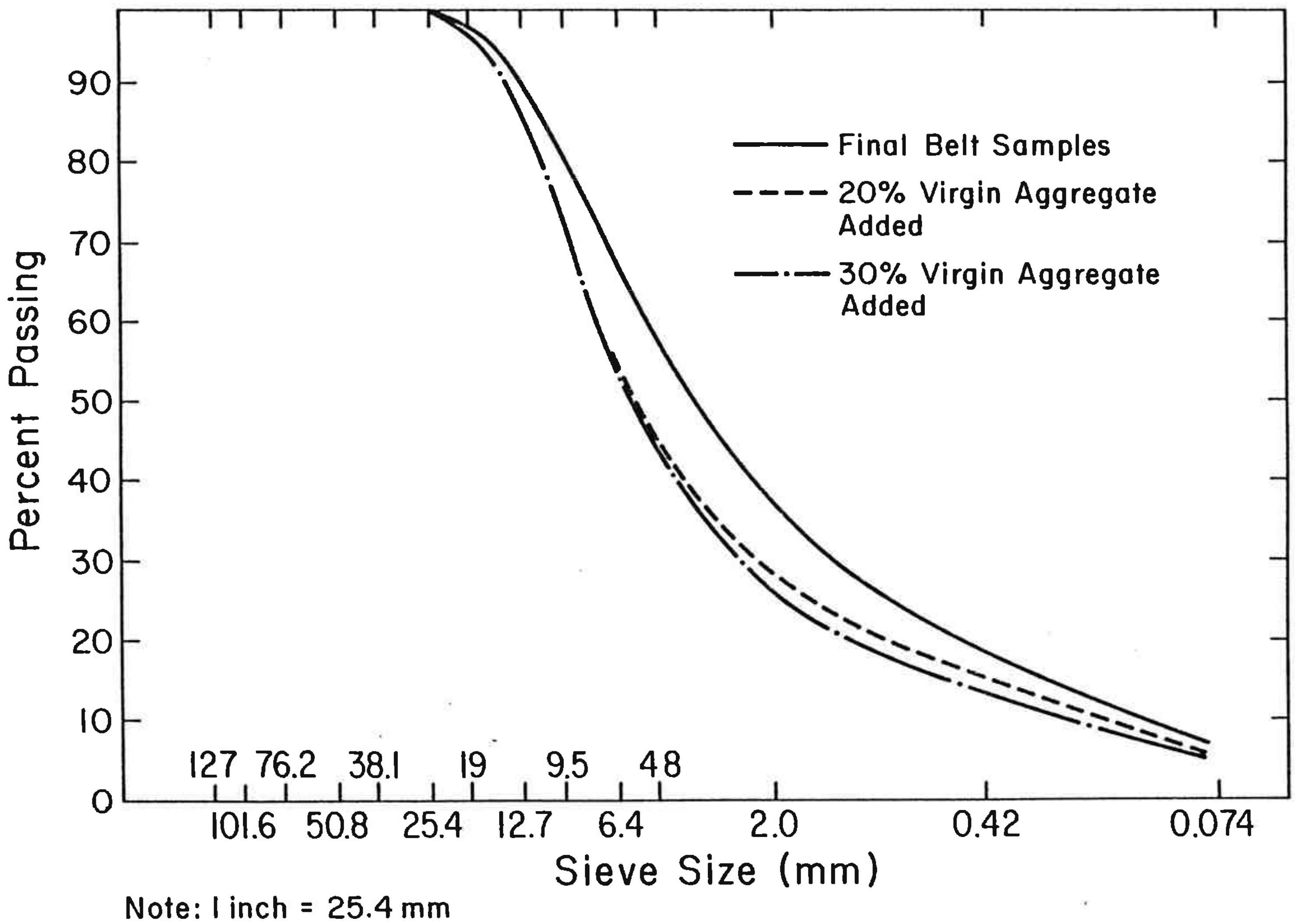


FIGURE 7. Average Gradation of Aggregate Material at the Final Belt Following Crushing and in the Street with the Addition of 20% and 30% Virgin 19 mm x 2 mm Aggregate

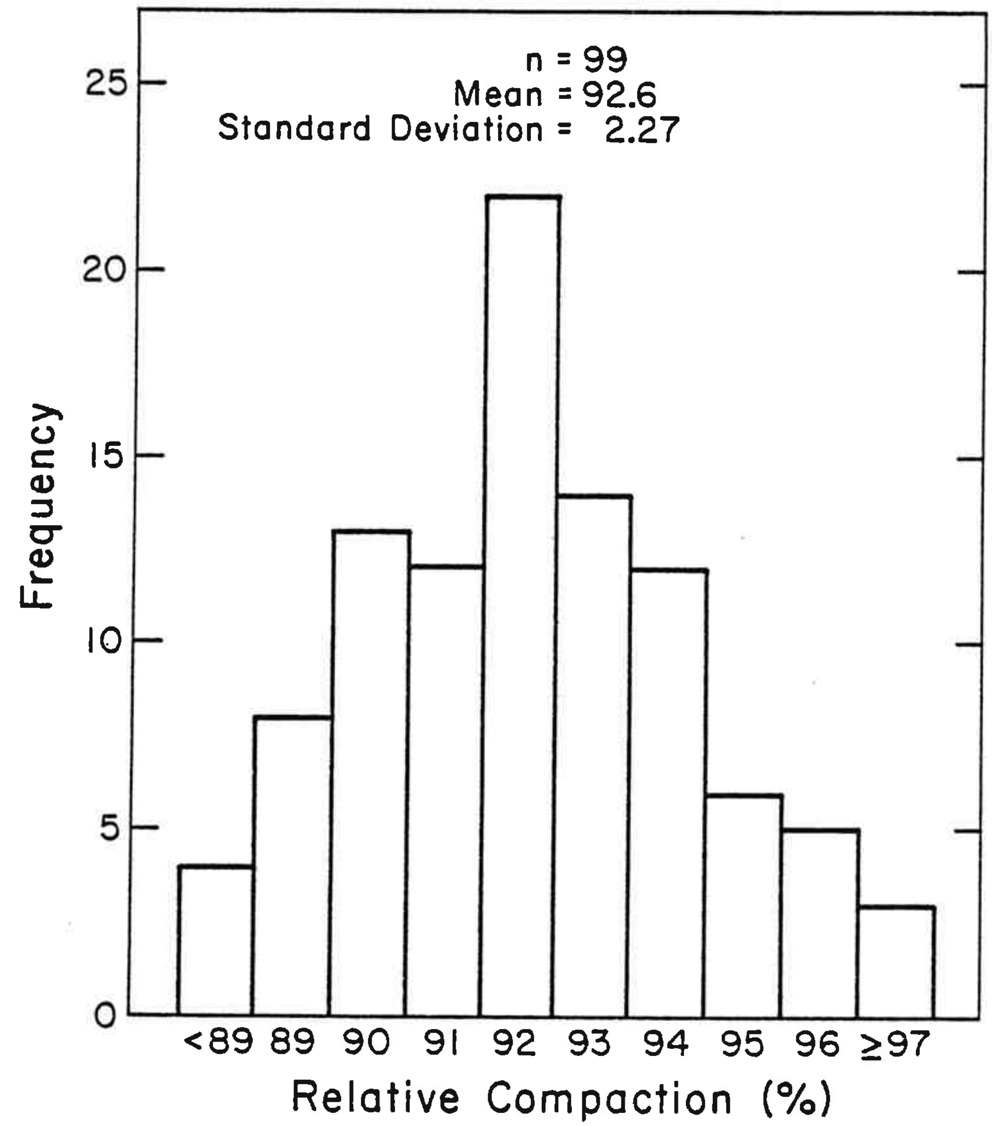


FIGURE 8. Histogram of Relative Compaction Achieved in the Project -- (Based on the Density of Field Cores Compares to the Density of the Mix Design Specimen at Second Compaction)