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COLD-RECYCLING OF ASPHALT PAVEMENT - U.S. 24
PROJECT CX-04-0024-25

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16. Abstract

The objective of this study was to evaluate the cold-recycling process and to determine the effectiveness of the three types of rejuvenating agents used in the cold-recyle mix. Additionally, two types of covers were used and were compared to determine their ability to seal the cold-recycled pavement.

Implementation

The study has shown cold-recycling to be an effective and valuable method for rehabilitating asphalt pavements and retarding reflective cracking.

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I. INTRODUCTION

Rising construction costs, depletion of aggregate supplies, and the need to conserve petroleum has created a need for cost efficient and energy saving methods for highway construction in Colorado. Each year a large portion of Colorado's money is spent on the rehabilitation of old asphalt pavements.

Historically, the State of Colorado has used one of two methods to rehabilitate old asphalt pavement. The most common method is the conventional Hot Bituminous Pavement (HBP) overlay over the existing pavement. In the second method, the existing pavement is removed and replaced with another asphalt pavement, using virgin aggregate and new asphaltic cement. More recently, however, the need for energy and natural resource conservation had led to the state's standard use of two additional alternatives -- hot asphalt pavement recycling. In the first process the existing pavements are heated, scarified to a specified depth, treated with a rejuvenating agent, and then re-compacted with a steel wheeled roller. An HBP lift is then placed as a wearing surface. In the second process, the existing asphalt pavement is removed, crushed and blended with new material in a central hot batch plant. This hot recycled material is then hauled back to the roadway and placed in the same manner as a new pavement.

Cold-recycling an asphalt pavement is an entirely different process and several different methods for cold-recycling are available. Except for a few small projects, the majority of cold-recycling in Colorado has been limited to the use of leftover crushed pavement as a cold mix for temporary road repair and shoulder widening by maintenance forces.

The objective of this study was to evaluate the cold-recycling process and to determine the effectiveness of the three types of rejuvenating agents used in the cold-recycle mix. Additionally, two types of covers were used and compared to determine their ability to seal the cold-recycled pavement.

II. LOCATION AND METHOD OF RECYCLING

This project, CX-04-0024-25, was located on U.S. 24 east of Colorado Springs between Peterson Field and Falcon. The project limits were between M.P. 312.50 and M.P. 319.90, and the existing pavement was 44 feet wide, from outside shoulder to outside shoulder, however, only the driving lanes were recycled. Figure 1 shows the location of the project.

This project is located on the eastern plains. The annual precipitation for Colorado Springs averaged 15.6 inches per year from 1986 through 1989. The extreme high and low temperatures for the evaluation period occurred in 1989 with 97°F on July 8 and -17°F on February 5. The temperature data during the evaluation period for Colorado Springs is shown below.

TEMPERATURE DATA

Colorado Springs
1986 - 1989

Year	Annual Precipitation	Extreme High	Extreme Low
1986	16.26 inches	95°F - Aug 8	-7°F - Feb 10
1987	18.23 inches	95°F - July 31	-11°F - Jan 17
1988	12.61 inches	95°F - July 23	-4°F - Jan 7
1989	15.44 inches	97°F - July 8	-17°F - Feb 5

The process of cold-recycling was consistent throughout this entire project and entailed milling off the top 2-1/2" of the existing asphalt mat. The material was then crushed, screened, mixed with an emulsified asphalt through a pugmill, and relaid all in one continuous operation. This was accomplished with a cold-recycling paving train consisting of three units which spanned approximately 100 feet in length. The first unit milled the pavement material to the required depth. This unit could mill a full lane width (12.5 feet) in one pass. Once the material was milled, it was carried on a conveyor belt to the next unit which contained a screening system. The screening system consisted of two sets of screens which separated the oversized material and redirected it into a hammermill where it was further broken up. From the hammermill the material was carried on another conveyor belt back through the screening system. This procedure was continued until the material passed the screening process (100% passing the 1-1/4 inch screen, 90-100% passing the 1 inch screen). The project specifications can be found in Appendix A.

Once the material was the proper size it was again carried on a conveyor belt to the third unit which contained the pugmill. The material was weighed on this belt before being carried into the pugmill. In the pugmill the emulsion was added according to the weight of the material carried on the belt. Because the emulsion was added according to the weight of the material carried on the belt, variations in the milling speed were possible. The material was in the pugmill between 30 to 60 seconds before it was windrowed on the roadway. The emulsion was supplied by a separate tank truck attached at the beginning of the train.

The windrow elevator attached to the laydown machine followed directly behind the paving train picking up the recycled material and placing it into the hopper. The rollers immediately followed the laydown machine.

A minimum of two hours following the rolling process was required before traffic was allowed on the recycled mat.

This paving train operation required a crew of five to operate: one person to operate the milling unit, one person on either side of the milling unit to maintain the proper milling depth, one person to control the proper mixing of the emulsion and one person to oversee the entire process to make sure everything was running smoothly.

Photographs of the paving process are shown in Photo 1 through Photo 6.

FIGURE 1

Project Location Map

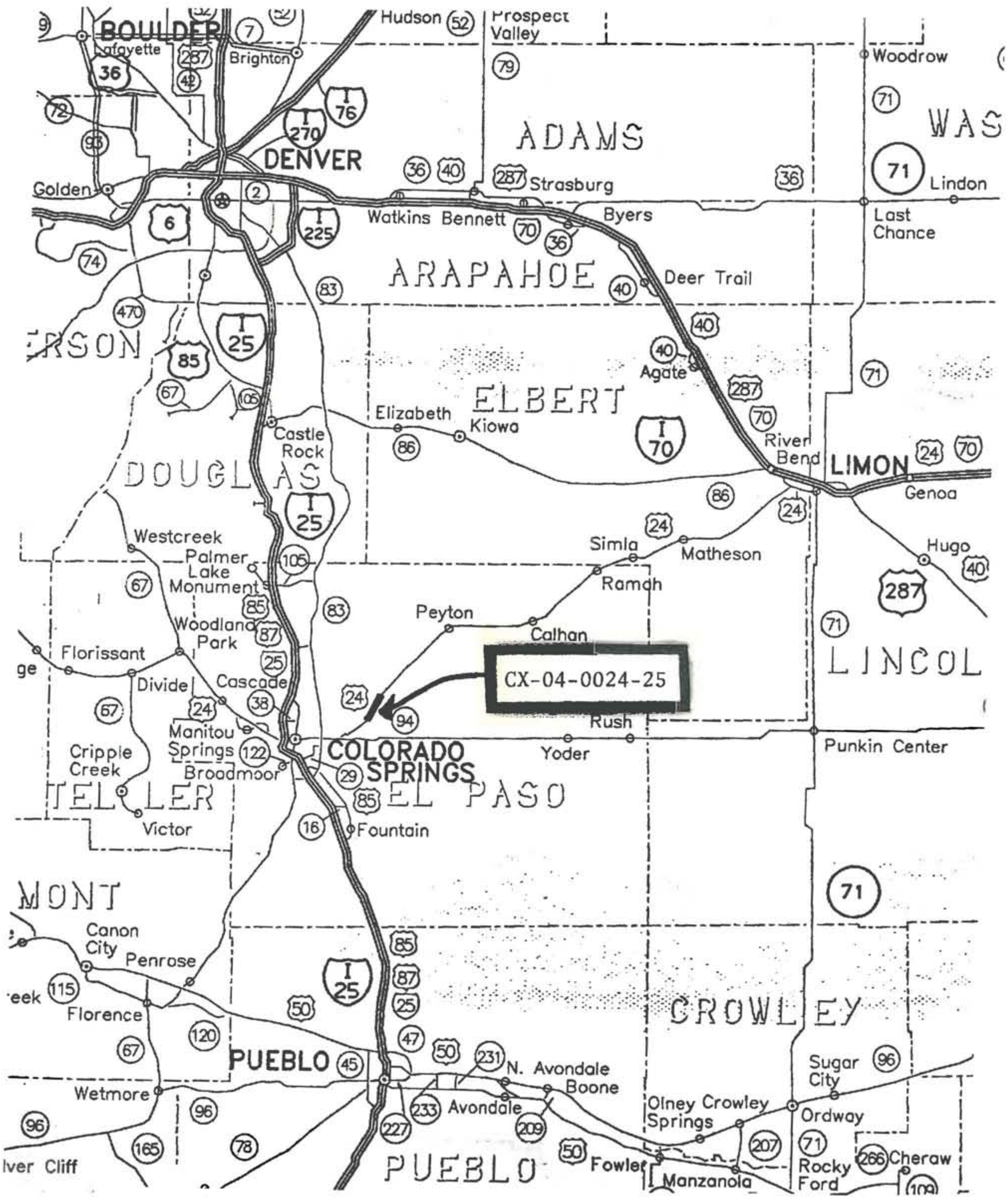


Photo 1

The paving train consisted of three units.

Photo 2

The first unit contained the milling chamber. The emulsion truck was attached to milling unit and pumped emulsion to the pugmill.

Photo 3

The second unit contained the screening and crushing system.

Photo 4

In the third unit the emulsion was added to the milled material and then placed on the roadway in a windrow.

Photo 5

The windrow elevator picked the material up and placed it in a hopper.

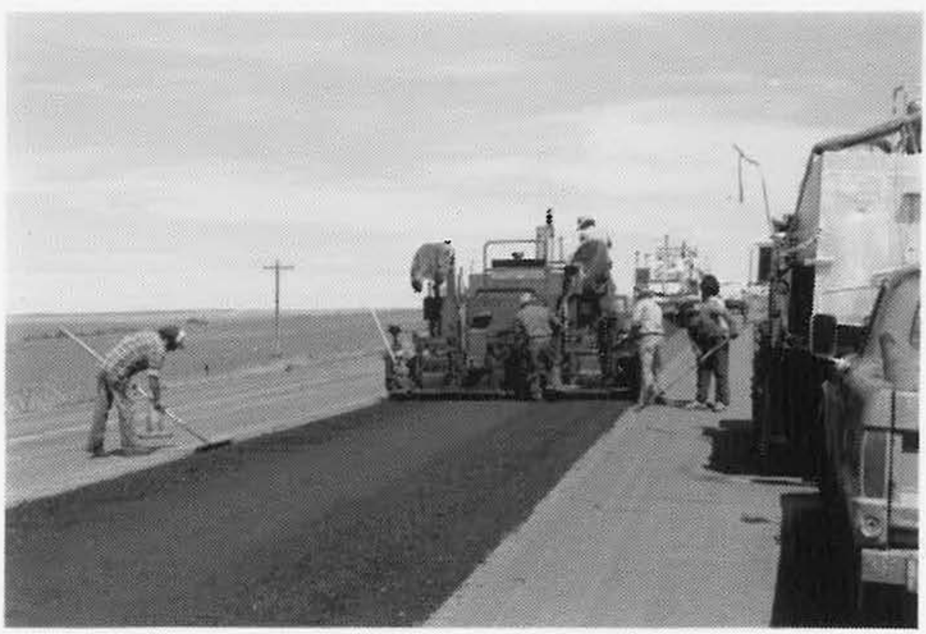


Photo 6

The lay-down machine followed directly behind the train.

III PRE-CONSTRUCTION ROADWAY CONDITION

The original roadway condition was severely distressed. The pavement on the west end of the project contained mostly transverse cracks with longitudinal cracking in the wheel paths. The majority of the cracks on the west end had been sealed by maintenance. The existing pavement on the east end was severely block cracked in both wheel paths. Very few of these cracks had been sealed. Typical pavement sections are shown in Photo 7 and Photo 8. The depth of the existing pavement varied from 2.5 inches to 5 inches.

Typically rutting is measured prior to construction, however visual observation showed that rutting was minimal and not significant, therefore rutting was not measured.

Photo 7

The original pavement on the west end of the project contained mostly transverse cracks with longitudinal cracking in the wheel paths. Most of the cracks had been sealed.

Photo 8

The original pavement on the east was severely block cracked. Very few of the cracks had been sealed.

IV. CONSTRUCTION

In accordance with the plans, the project was divided roughly into halves. On the east end, between M.P. 316.5 and M.P. 319.9, the contractor placed a 1-inch HBP overlay over the entire roadway width; however, only the driving lanes were recycled in this section. On October 8, 1989, the planned chip seal was placed on the west end by maintenance forces on the driving lanes between M.P. 312.5 and M.P. 316.5. The shoulders in this section were chip sealed on October 16th.

Cold-recycling Operation

The cold-recycling process began September 15, 1986 at M.P. 314.51. Starting in the eastbound lane, in the direction of travel, a 12-foot 6-inch pass, 2.5 inches deep section was milled.

The depth of the cut was controlled by a pivoted four foot ski on wheels attached to a sensing device which measured changes in the grade of the roadway. The depth was checked manually every few feet and depths were adjusted according. The depth was controlled in the same manner on both sides of the milling machine. This is shown in Photo 9.

The paving train travelled between 28 to 40 feet a minute and processed approximately 300 tons of material a hour. An average of two miles of one-lane roadway were milled during a 10 hour day.

Recycling Agents

The initial percentages of emulsions to be added to the recycled material were determined from tests conducted on the existing pavement. These percentages changed depending on how the material looked once it was milled and the emulsion was added. Most of the emulsion percentages were increased once the process began because the recycled pavement appeared to be too "dry" and began to ravel under traffic. Raveling to some extent occurred on all of the test sections. This was apparent from the fines scattered on the shoulders and down the center of the roadway. This is shown in Photo 10. Raveled sections were covered with a fog seal of CSS-1h to prevent further raveling. A chip seal was placed on the recycled sections containing three types of emulsions used in the recycling process, CSS-1h modified, HFMS-2sP and Cyclogen ME. On the east end, a 1-inch HBP overlay was placed over the recycled sections. The recycled material contained two types of emulsions, HFMS-2sP and Cyclogen ME.

The three types of emulsions used on this project were:

HFMS-2sP - This is a polymer-modified high-float emulsion. A minimum of 3% polymer is blended with the base asphalt, then it is emulsified into a high float emulsion. The penetration on the residual asphalt is greater than 150.

This material is used in cold-recycling because the soft asphalt (150+ pen) helps to soften the old mat, and the addition of the polymer greatly aids in the adhesion of the milled pavement.

Cyclogen-ME - This is a modifying or rejuvenating agent which is incorporated into an emulsion to aid mixing. This product is a mixture of maltenes and regular asphalt cement. The maltenes are the resinous components of an asphalt cement which, when mixed with the milled pavement, help restore the old asphalt in the pavement to an un-aged condition. The asphalt portion aids in binding and coating the milled pavement.

CSS-1h Modified
Penalizer - This product is a high-ductility asphalt cement blended with a very hard pitch and then emulsified to enhance mixing in a cold-recycle application. The end result of

this blend of materials is a pavement which has a high stability because of the hard "pitch" portion, and also a high ductility from the asphalt portion. The high ductility is intended to resist thermal/transverse cracking in the recycled pavement.

Table A contains the final percentages of emulsion that were added in each section. A map of the project with the percentages in each section is shown in Figure 2.

Traffic Control

During construction, traffic was controlled by allowing only one direction of travel through the construction area at a time. Traffic on either end was only delayed for short periods of time. Traffic was allowed on the recycled pavement two hours after processing.

Weather

The weather was very cooperative throughout the process. There was not any rain or snow during the process. The temperature was always above the temperature required (minimum of 50^{o}F) during the cold-recycling process. Without bad weather during construction there was not an opportunity to test the weather sensitivity of the process.

Rolling Pattern

The first day the rollers stayed fairly close to the laydown machine. A pnuematic roller was used for break down and required seven passes. This was followed by four passes with a vibratory roller. The finish roller (steel-wheeled roller) passes varied from four to eight depending on the density reading. The density readings from the nuclear gauge on the first day were low and originally the calibration of the gauge was suspect. It was also felt that the rollers might be rolling too fast. The following day the rollers were held back; however, this did not make a difference in measured density. The next day the specific gravity of the new material was recalculated and compaction was acceptable.

Several portions of the cold-recycled pavement processed on the first day did not lay down smoothly and approximately 100 feet throughout this area had to be leveled with a blade. Photo 11 shows the texture of a typical section following cold-recycling.

Asphalt Overlay

The area that was overlaid with one inch of HBP was from M.P. 316.5 to M.P. 319.9 and included the un-recycled shoulders. Before the overlay could begin, the percentage of water in the recycled mat was specified to be within one percent of the water content in the original pavement.

Originally it was thought that the water content of the existing material could be determined from the milled material prior to adding the emulsion. However, water was added in the milling process which precluded using this method. A sample of the recycled material was dried and the water content was calculated to verify that the water content was low enough to begin overlaying. Before the overlay began the percentage of water in the recycled mix, using this method, was between 0.8% and 0.7% and within specifications.

The HBP overlay portion (M.P. 316.50 to M.P. 319.90) of this project was completed on September 22, 1986. On October 8, 1986, when weather permitted, a chip seal was placed by maintenance on the west end between M.P. 312.5 and M.P. 316.5.

Photo 9

The depth of the cut was checked manually every few feet and adjusted accordingly on both sides of the milling unit.

Photo 10

The rapid raveling of the new mat was shown by the fines scattered on the shoulder.

TABLE A

Percent Of Emulsion Used In Each Section

Direction of Lane	Mile Posts	Type of Emulsion	Percent of Emulsion (by weight)	Depth of recycling (in)
EB	312.50 to 312.70	CSS-1h (modified)	2.5	2.5
"	312.70 to 312.76	**		
"	312.76 to 314.36	Cyclogen ME	2.0	2.5
"	314.36 to 314.51	**		
"	314.51 to 316.50	HFMS-2sP	2.5	2.5
"	316.50 to 318.05	HFMS-2sP	1.5	2.5
"	318.05 to 318.17	**		
"	318.17 to 319.50	Cyclogen ME	1.5*	2.5
"	319.50 to 319.90	Cyclogen ME	1.5	2.0
WB	319.90 to 318.17	Cyclogen ME	1.5	2.5
"	318.17 to 318.05	**		
"	318.05 to 316.70	HFMS-2sP	2.0	2.5
"	316.70 to 314.65	HFMS-2sP	2.5	2.5
"	314.65 to 314.51	HFMS-2sP	2.0	2.5
"	*** 314.75 to 314.51	HFMS-2sP	2.5	2.5
"	314.51 to 314.36	**		
"	314.36 to 312.76	Cyclogen ME	2.0	2.5
"	312.76 to 312.70	**		
"	312.70 to 312.50	CSS-1h (modified)	2.5	2.5

* First 100 feet of this section only contained 1% of emulsion by weight.

** These areas were not recycled.

*** This area was in the turning lane for Constitution.

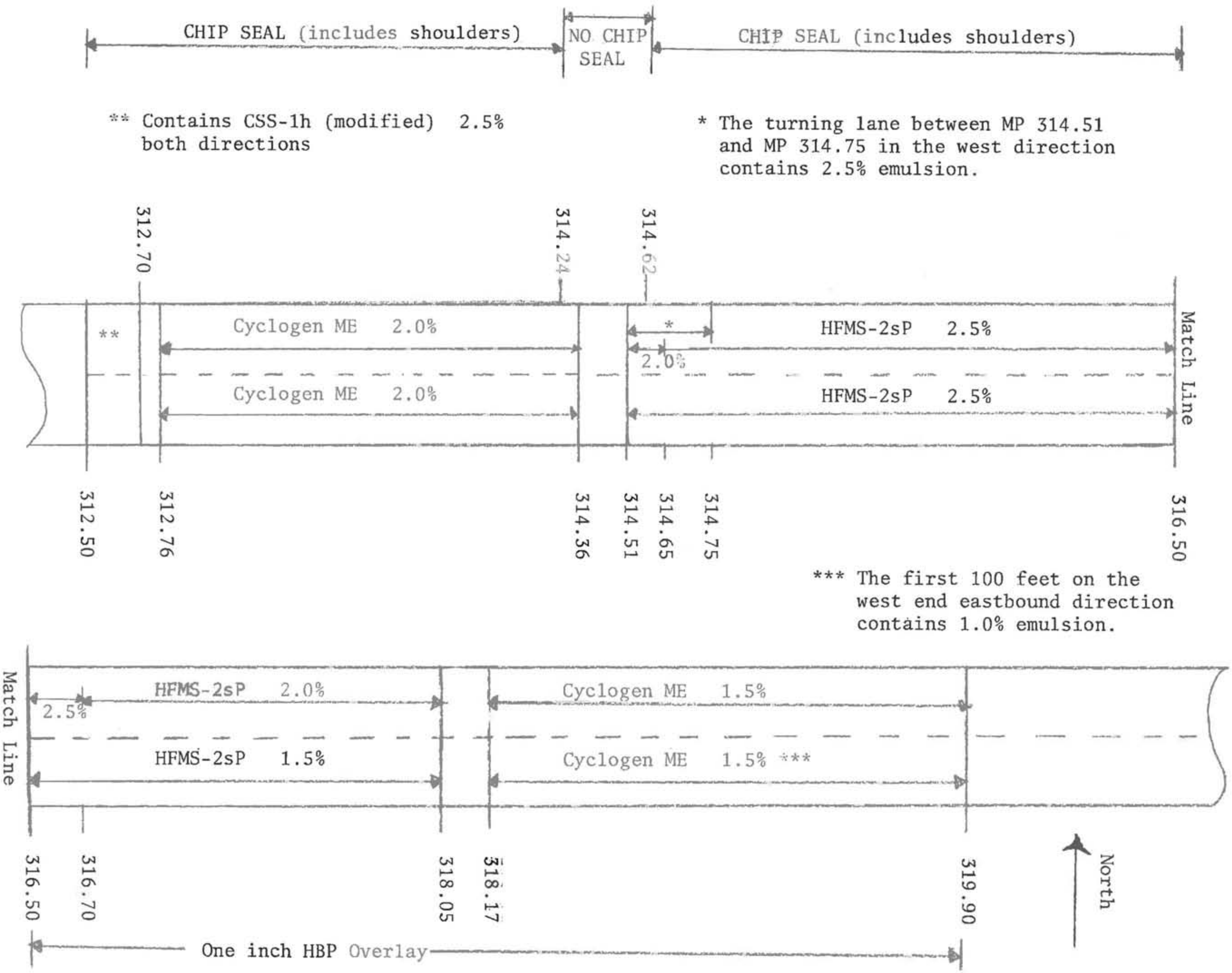


FIGURE 2
Emulsion/Application Rate Locations

V. CONSTRUCTION EVALUATION

Since this was the first time a process of this type was used in Colorado, a number of adjustments were made during the recycling process. Several construction problems were encountered during construction of the project.

During construction, only one of the emulsion caused the contractor problems. The CSS-1h modified which was required in both directions in the first 1000+ feet on the west end of the project was difficult to work with because it hardened too quickly. This section was recycled in two passes, the eastbound lane was recycled in the west direction first. When turning the paving train around, to finish the westbound direction, the emulsion hardened in the pipes. This caused difficulty when adjusting the flow rate of the emulsion for the westbound lane. The first 50± feet of this section received too much emulsion which then had to be removed.

After the CSS-1h modified material was rolled the mat looked good. The condition of the mat can be seen in Photo 12. The following morning after traffic had driven on the recycled mat, the roadway began to ravel badly. Two fog coats of CSS-1h were applied to this section. The project engineer decided to overlay the entire CSS-1h modified section before it raveled out completely.

Raveling of the recycled material was a problem in all the sections, especially in the sections where the paving train stopped, either to switch to a new additive or at the end of a day's operation. Due to the nature of the cold-recycling process, material left by the pugmill did not contain enough emulsion resulting in these sections raveling more than the other sections.

The cold-recycling process consisted of a moving paving train. At the beginning of a section, the material milled was conveyed through the screening and crushing system and pugmill. The recycled material was ready for placement before reaching the milled section. For this reason whenever the paving train started a new section more material was milled than could be placed. This extra material was hauled to the end of the section. At the end of each section material left by the paving train was mixed with the excess material hauled from the beginning of the project. This typically was placed within the last 20 feet of the section. When traffic was permitted on the recycled pavement that contained this remixed material it began to ravel more rapidly than the remaining roadway.

Eventually, the entire project had to be covered with a fog seal of CSS-1h to prevent further raveling. One of the raveled sections is shown in Photo 13.

Another problem that was noticed during construction was the presence of oily sand pockets in the new mat throughout the project. It is not known how these sand pockets were created, but from the time the pavement was milled to laid down, clumps of sand appeared in the mix after the laydown operation and were spread out with the laydown machine.

Once traffic was permitted on the recycled mat the sand pockets raveled out and caused circular depressions in the new pavement. These sand pockets occurred regardless of the binder used and are shown in Photo 14 and Photo 15.

Delays caused by the paving train were minimal. Due to the abrasive aggregate in the pavement, and since the amount of water used to mill the material was limited to keep the water in the new mix low, the teeth needed to be changed approximately three times a day. This process took between 30 minutes to 45 minutes depending on the number of teeth that needed to be replaced. Milling teeth are shown in Photo 16.

On the third day of recycling longer augers were placed in the laydown machine for better distribution of the milled material to the outside edges. The shorter augers had not caused any immediate problems. However, with the shorter augers the milled material was not being distributed evenly to the outside edges which could eventually lead to premature pavement deterioration.

In addition, portions of the road were so badly cracked that the material was milled into large chunks causing the crushing section of the machine to clog up. Several times the milling was stopped to unclog the hammermill. The larger pieces of the milled material forced the hammermill to work extra hard when crushing the material into the proper size causing the speed of the paving train to be reduced. Even though the machine had difficulty with milling the large chunks, the size of the material in the windrow was within specification. The milled material is shown in Photo 17 and Photo 18.

Photo 12

This is a photo of the CSS-1h modified immediately following the rolling process. The following day this section was overlaid because it began to ravel.

Photo 13

This photo shows the end of a section which raveled after traffic was allowed on it.

Photo 14

This photo shows one of the oily sand pockets found throughout the project.

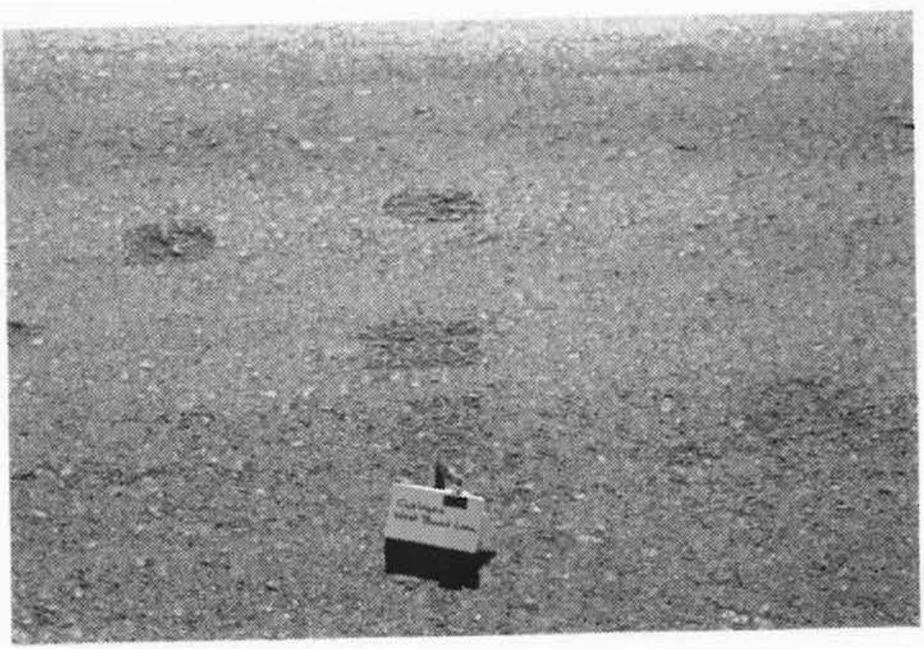


Photo 15

After traffic had driven on the cold recycled roadway the sand pockets raveled out leaving circular depressions in the pavement.

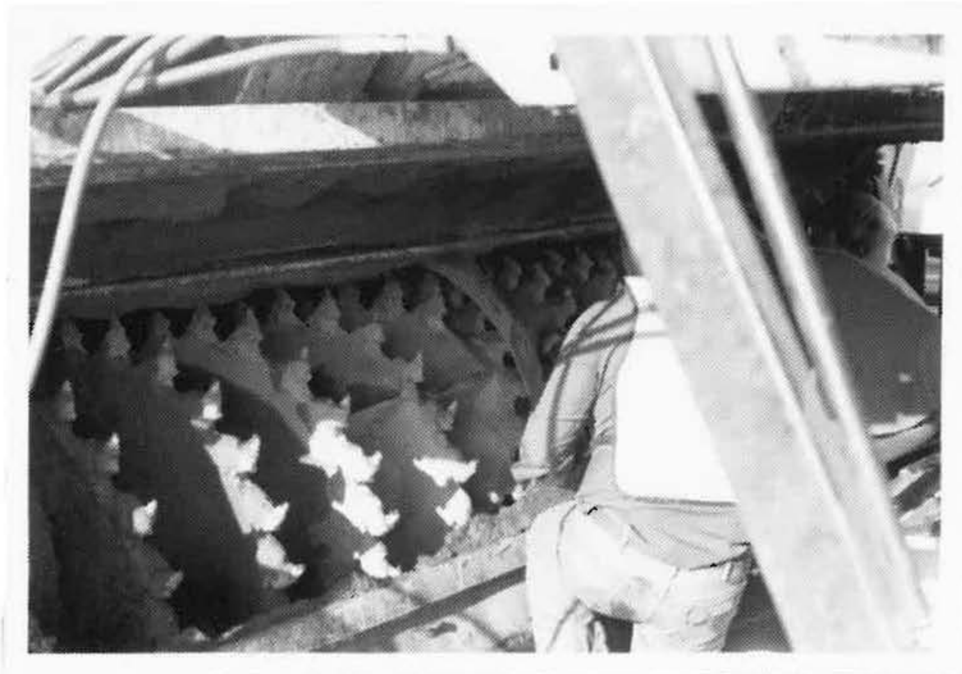


Photo 16

The teeth on the milling machine were changed three times a day.

Photo 17

The milled material in the windrow.

Photo 18

Texture of the milled material. This material met the specification for gradation.

VI. EVALUATION SECTIONS

As referenced in the construction section of this report, the project was divided roughly into halves. One-half of the recycled mat was covered with a chip seal, the remaining portion was covered with a 1-inch HBP overlay.

For comparison purposes three different emulsions were used in the recycling process under the chip seal. Two of these emulsions were used in the recycling process under the 1-inch HBP overlay. Table B lists the section, type of emulsion used for the cold-recycling process, and the type of cover placed on top of the recycled mat. Figure 3 contains the location of each evaluation site.

Prior to construction, two 600 foot evaluation sections were established in each section to evaluate the different emulsions used in the recycling process for both the chip sealed and overlaid sections.

The project also contained three additional evaluation sections which were established to determine the performance of the recycled material. One section of the cold-recycle was left uncovered to help determine the performance of the material under traffic. To help determine to what extent the cold-recycled material increased the overall pavement performance two sections were not recycled, one section was covered with a chip seal, the other with a 1-inch HBP overlay.

An additional evaluation section was established at each location to provide a backup section. These sections were established in case the initial evaluation sections were not representative of the cold-recycling process. Both the primary and secondary sections were evaluated during the entire study, unless there were problems within a section which prevented an objective evaluation on the cold-recycled material.

Pre-construction evaluations were performed at selected sites. These evaluations included deflection measurements and a visual inspection of the cracking and rutting.

During construction the evaluation on the CSS-1h modified section (1 and 1A) was discontinued. This section raveled extensively after the cold-recycling process and prior to a surface treatment. This area was overlaid with HBP immediately to prevent losing the entire section. The evaluation on this section was eliminated as it would not be representative and not comparable to the remaining recycled sections.

Following construction two evaluation sections (5A and 6A) were deleted because of construction problems unrelated to the cold-recycle process. Section 6 was reestablished from the eastbound lane to the westbound lane.

Prior to the first spring evaluation, section 4A had to be deleted from the evaluation process. This recycled section did not receive a cover and was left exposed during the winter months and extensive patching was needed during the winter months.

During the summer months of 1987, the recycled pavement which was covered with a chip seal became soft and under traffic the chips were forced into the pavement creating a smooth surface. To reduce the hazardous conditions created during wet weather, maintenance crews sanded this section throughout the summer. The sand placed on the roadway eventually increased the surface roughness and with the onset of lower temperatures, the hazardous condition (low skid resistance) was reduced. However, since the same situation was expected to occur the following summer, the chip sealed section was overlaid with HBP. Evaluation on sections 2, 2A, 3, 3A and 6 was discontinued because of this failure.

Section 4 and section 5 were cold-recycled; however, these sections did not receive a cover material until the summer following construction. At that time they received 1-inch HBP overlay. Prior to these sections being overlaid the recycled material raveled extensively. It was concluded that stage construction for this type of rehabilitation is not feasible and the evaluation of these sections were discontinued.

One year following construction the only sections still being evaluated were the sections which received the 1-inch overlay during construction. This included sections 7, 7A, 8, 9, and 9A.

Comprehensive evaluations continued on the remaining sections through the spring of 1989. These evaluations included deflection measurements, rut depth measurements, smoothness tests, core sampling and visual observations. A final evaluation was made in the spring of 1990 and was limited to visual observations.

TABLE B

Summary Of Evaluation Sections

*Evaluation Section	Type of Additive	Type of Cover
1, 1A	CSS-1h (modified)	Chip Seal
2, 2A	No Recycle	Chip Seal
3, 3A	Cyclogen ME	Chip Seal
4, 4A	Cyclogen ME	No Cover
5, 5A	HFMS-2sP	No Cover
6, 6A	HFMS-2sP	Chip Seal
7, 7A	HFMS-2sP	1" HBP
8, 8A	No Recycle	1" HBP
9, 9A	Cyclogen ME	1" HBP

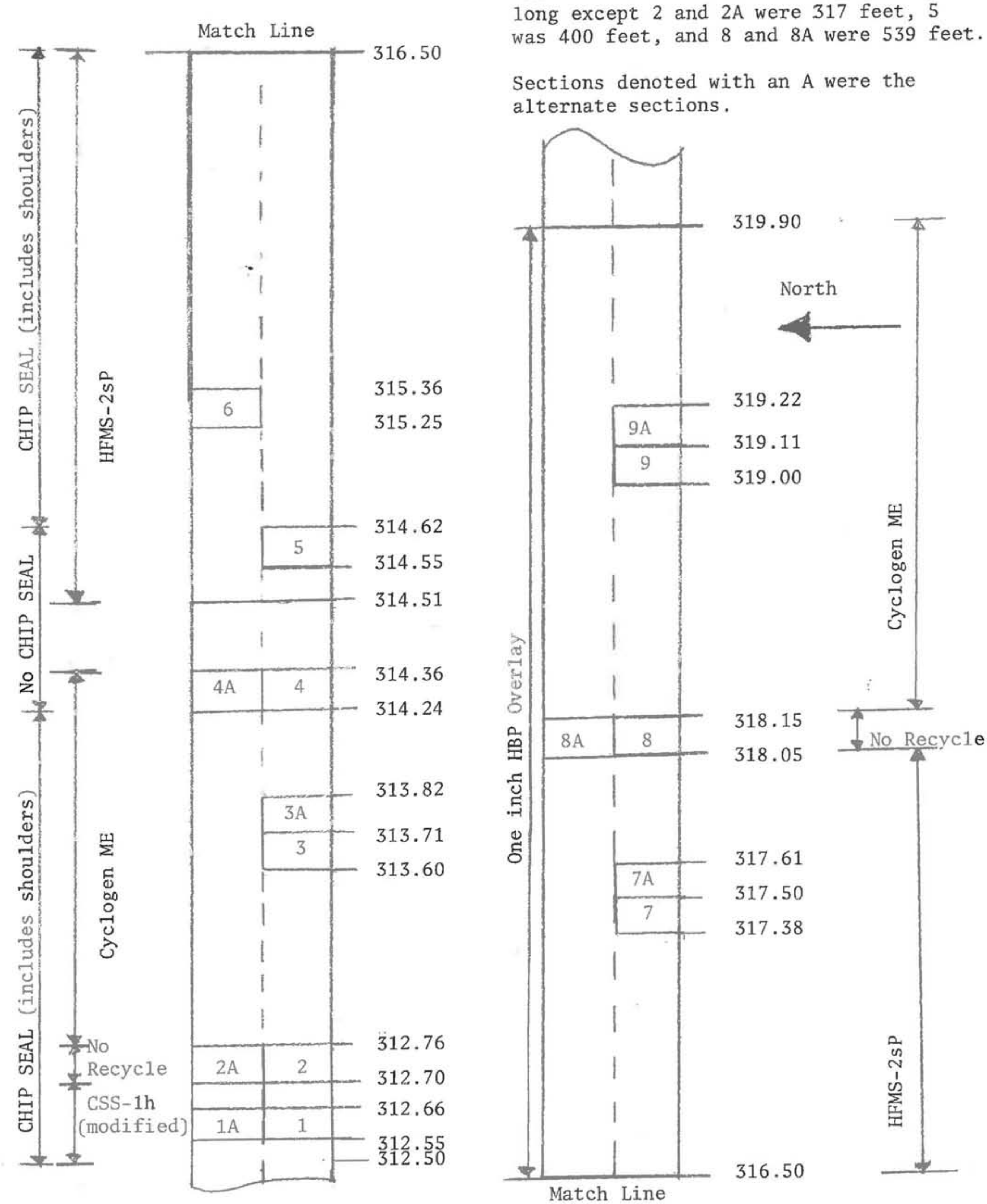
* Only evaluation sections 7, 7A, 8, 9, and 9A were evaluated the entire study.

FIGURE 3

Evaluation Site Map

All evaluation sections were 600 feet long except 2 and 2A were 317 feet, 5 was 400 feet, and 8 and 8A were 539 feet.

Sections denoted with an A were the alternate sections.



VII. TEST RESULTS

Several different parameters were examined to evaluate the cold-recycling process. Field measurements were made to determine the amount of cracking, deflections, roughness, and rutting. Laboratory testing was performed to determine stability, Lottman, and voids.

Cracking

Crack mapping of the first 100 feet of each section was done in the fall of 1987, and during the spring of 1988 and 1989. Crack maps of the entire sections were made during the 1989 evaluation. These full section maps verified that the first 100 feet crack maps were representative of the entire test sections. Comparisons were made between the various sections to determine the rate of cracking based on the type of emulsion used and the cover treatment.

The amount of cracking during the evaluation showed a significant difference between the cold-recycled sections with a 1-inch HBP overlay and the section which received only the 1-inch HBP overlay. After the first winter, the cracking pattern appearing in the section which received only the 1-inch overlay was extensive and similar to the cracking found in the original mat. Cracking in the cold-recycled portion was minimal; however, cracks were reflecting through on the shoulders in this area (the shoulders were not recycled on this project). It was observed that the majority of the shoulder cracks either stopped at the driving lane where the recycled material began, or extended only a few inches into the recycled mat. This can be seen in Photo 19.

Longitudinal, transverse, and block cracking were measured. During the evaluation of this project cracking appeared sooner and increased at a more rapid rate in the section which received only the 1-inch overlay (section 8).

Section 8, which received only the 1 inch overlay, was the only section that developed block cracking during the evaluation period. The cold-recycled sections which received the 1-inch overlay (sections 7, 7A, 9 and 9A) showed transverse cracking with minimal longitudinal cracking. In the cold-recycled section there was longitudinal cracking in the left wheel path which appears to be load associated. A summary of the total amount of cracking found in the evaluation sections is contained in Table C.

Deflections

The Research Branch's Dynaflect was used to measure pavement deflections. Measurements were made at 50 foot intervals throughout each test section, and only the sensor directly beneath the load was used for evaluation purposes. Deflection measurements were taken prior to construction, immediately following construction, and in in the spring of each year following construction. Graphic representation of deflection results can be seen in Figure 4 and Figure 5.

Changes in the deflection values, prior to construction and in the following spring were not noted. This indicates that the load carrying capacity of the pavement was not affected by the cold-recycling process (i.e. cold-recycling with the 1-inch HBP overlay). The deflection readings recorded at the conclusion of the study were approximately the same as taken prior to construction.

Roughness

A Rainhardt profilograph equipped with a 2/10 inch mechanical filter was used to measure the roughness of the pavement. Measurements were taken in both wheel paths of each section. Colorado currently does not have a asphalt pavement smoothness specification. The final profilograph readings using the 2/10 inch mechanical filter ranged from 0.9 inches\mile to 9.7 inches\mile. Even though a leveling operation was not used in conjunction with the paving, the profilograph readings indicate that the final pavement surface is smooth and within acceptable limits. The smoothness criteria for this asphalt pavement was determined to be in the medium smoothness range based on data derived from the pavement profile measurement seminar held on October 5-8, 1987.[1]

Rutting

Rutting measurements were taken in the spring and fall of 1987, and in the spring of 1988 and 1989. During each evaluation period these measurements were taken with a six-foot straight edge, in both wheel paths, at 50-foot intervals throughout the test sections. Visual observations prior to construction indicated rutting was minimal and therefore not measured. At the conclusion of this study no measurable rutting in the cold-recycled sections was noted.

Laboratory Results

Cores were taken immediately following construction, and once a year during the evaluation period. The percent voids in the cores taken in the recycled sections ranged from 12.0% to 16.6%. At the conclusion of the study the average voids in the recycled sections was 14.6%. With the high percent of voids, low Hveem stabilities values[2] (average 14) and based on the 1988 Average Daily Traffic (ADT) of 5250 (8.4% trucks) it would not have been unusual for rutting to occur.

The test results from the cores taken in the spring of 1989 for sections 7, 7A, 8, 9 and 9A can be seen in Appendix B.

Photo 19

Following the first winter the majority of the transverse cracks either stopped at the driving lane where the recycled material began or extended only a few inches into the recycled mat.

TABLE C

Summary Of Cracking

Pre-Construction

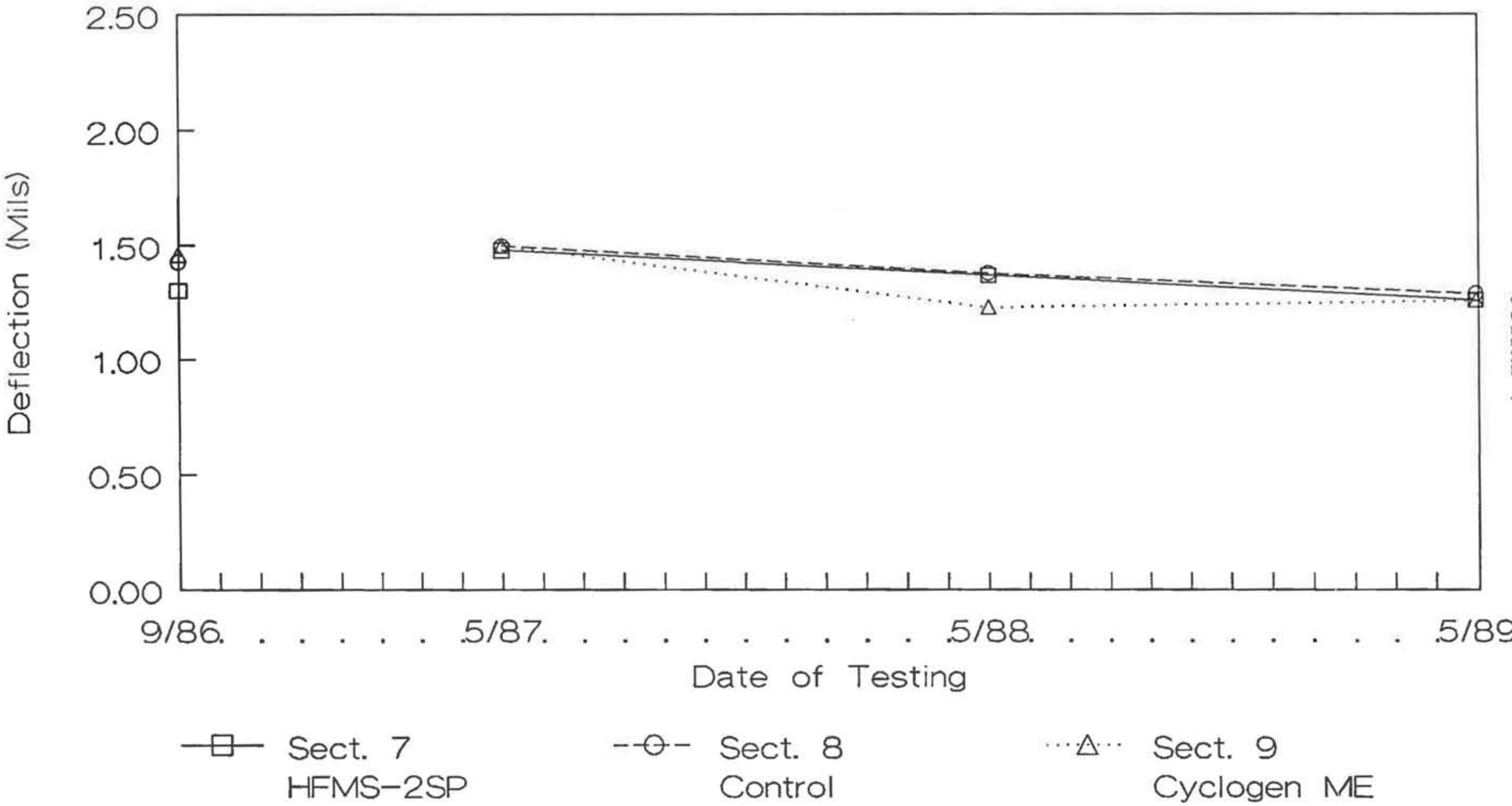
Section 7 -- Extensive cracking of all types
Section 7A -- Extensive cracking, mostly in the left lane
Section 8 -- Extensive cracking of all types
Section 9 -- Extensive cracking, mostly transverse
Section 9A -- Mostly block cracking

Post-Construction First 100 feet of evaluation section
Eastbound driving lane

	10/23/87	5/9/88	5/2/89
Section 7 -- HFMS-2sP			
Transverse (ft)	18	36	41
Longitudinal (ft)	0	32	68
Block (sq ft)	0	0	0
Section 7A -- HFMS-2sP			
Transverse (ft)	13	24	24
Longitudinal (ft)	0	0	22
Block (sq ft)	0	0	0
Section 8 -- No Recycle			
Transverse (ft)	160	219	225
Longitudinal (ft)	90	142	43
Block (sq ft)	26	58	237
Section 9 -- Cyclogen ME			
Transverse (ft)	2	35	50
Longitudinal (ft)	0	0	0
Block (sq ft)	0	0	0
Section 9A -- Cyclogen ME			
Transverse (ft)	3	3	72
Longitudinal (ft)	0	0	5
Block (sq ft)	0	0	0

** Dynaflect Readings

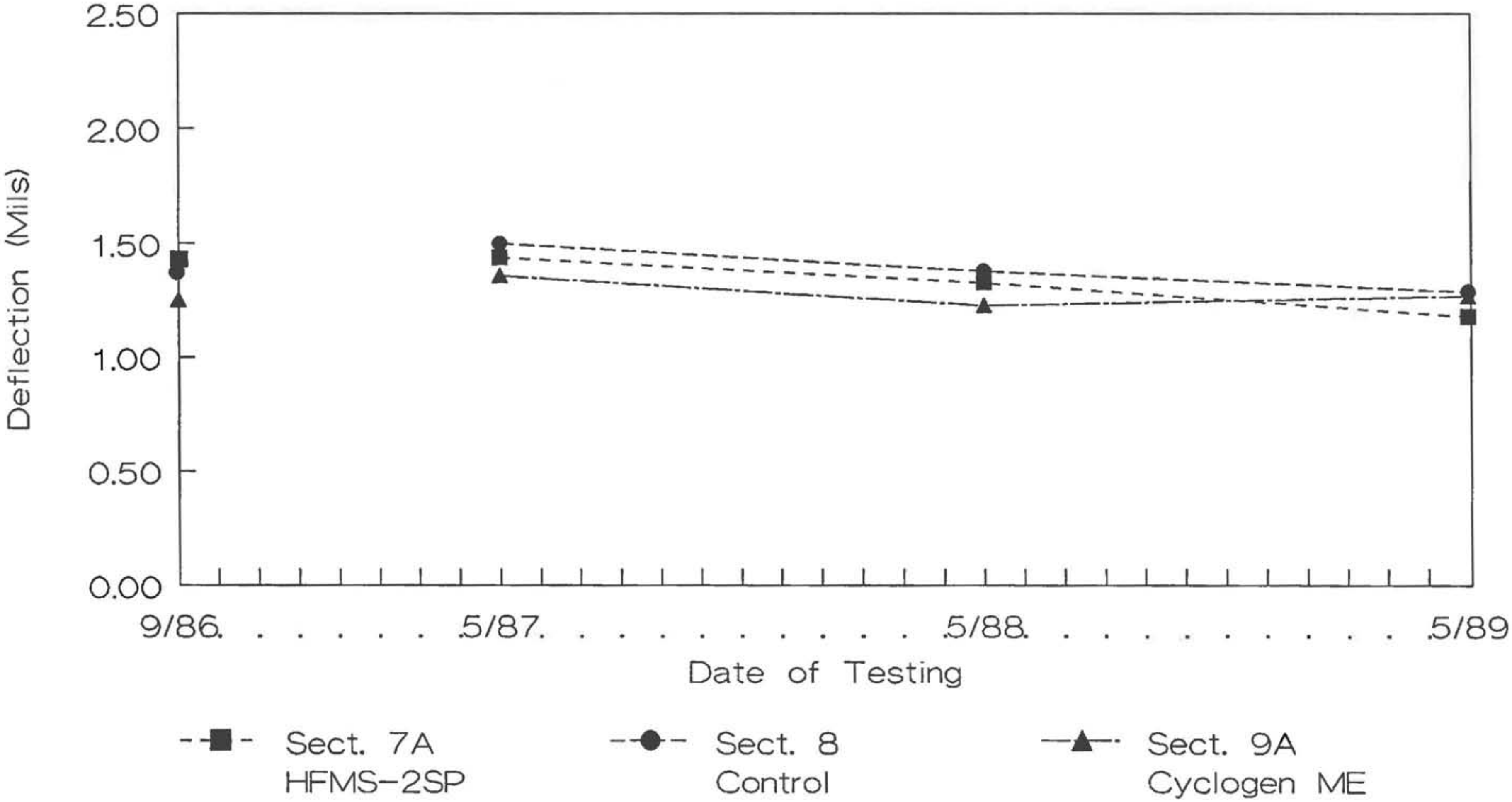
Sensor No. 1, Sections 7, 8, and 9



** Dynaflect readings were corrected to 70°F

FIGURE 4

** Dynaflect Readings
Sensor No. 1, Sections 7A, 8, and 9A



Dynaflect readings were corrected to 70°F

FIGURE 5

VIII. COST ANALYSIS

As part of this study an economic cost analysis of the cold-recycling process was made. In addition to the cold-recycling method, Table D contains two equivalent rehabilitation alternatives used for comparison on this project.[3] The alternatives were selected based on the condition of the existing pavement. The alternatives selected for comparison were:

1) a 3-1/2" of HBP with a geotextile interlayer (the existing pavement contained cracking which past experience has shown that fabric interlayers help to control) and
2) a 3-1/2" HBP overlay.

For design, the strength coefficient used for cold-recycling was established at 0.25 and for the HBP overlay the strength coefficient is 0.44. For comparison purposes the total pavement section of the HBP and that of the section using cold-recycle and HBP was calculated at 3-1/2".

This analysis indicates that for this project cold-recycling saved 35% when compared to the 3-1/2" HBP overlay and 50% when compared to the 3-1/2" HBP overlay with the geotextile interlayer.

In addition to the cost savings which cold-recycle can provide over conventional rehabilitation methods, additional savings can be realized through:

1) savings in crushing, processing, and hauling virgin materials;
2) savings in utilizing existing asphalt material; and
3) conservation of resources which in the eastern plains of Colorado is a major concern because of the lack of quality aggregates

TABLE D

Cost Comparisons For Alternatives
Project CX-04-0024-25

1. <u>Cold-recycle Method</u>

Cold Bituminous Pavement (recycle)
Application Rate:

Cyclogen ME	2.4% by weight
CSS-1h (modified)	3.0% by weight
HFMS-2sP	3.0% by weight

Project Costs

Cost of cold-recycle	$1.20/sq yd
Cost of Cyclogen ME	$0.95/sq yd
Cost of CSS-1h (modified)	$0.99/sq yd
Cost of HFMS-2sP	$0.87/sq yd
Cost of 1" HBP cover (Grading EX) (Haul and Asphalt)	$1.37/sq yd/in

<u>Based on 2-1/2" of cold-recycle and 1" HBP overlay</u>

Cost of cold-recycle using Cyclogen ME	**$3.52/sq yd**
Cost of cold-recycle using CSS-1h (modified)	**$3.56/sq yd**
Cost of cold-recycle using HFMS-2sP	**$3.44/sq yd**

2. <u>3-1/2" HBP Overlay With A Geotextile Fabric Interlayer</u>

Project Costs

Cost of 1" of HBP (Grading EX) (Haul and Asphalt)	$1.37/sq yd/in
Average Cost of Geotextile Fabric (taken from 1986 cost data book)	$0.51/sq yd

Average cost of 3-1/2" of HBP with a geotextile fabric interlayer	**$5.31/sq yd**

3. <u>3-1/2" HBP Overlay</u>

Project Costs	$1.37/sq yd/in
Cost of 1" of HBP (Grading EX) (Haul and Asphalt)	

Cost of 3-1/2" of HBP	**$4.80/sq yd**

XI. CONCLUSIONS

The specially designed paving train used for this project was very efficient. It was able to process an entire traffic lane (12.5 ft) in one pass with little disruption to the normal traffic flow. Traffic was permitted on the recycled mat after a minimum of two hours.

Given the length of the paving train (100 feet plus) this process is best suited for interstate and rural projects.

The process recycled 300 tons an hour which is comparable to HBP. Except for the expected paving delays, such as changing the milling teeth, little time was spent on machine adjustments.

From a safety standpoint, the cold-recycling process does not produce any drop offs which remain overnight. This eliminates a safety hazard which is generally associated with conventional pavements.

It is also felt that by allowing traffic on the cold-recycled mat potential subgrade failures will be detected prior to the overlay. These failures can be repaired before the overlay and not become a maintenance type repair after the completion of the project.

There were no significant differences in the performance of the recycled sections which contained the different emulsions - HFMS-2sP and Cyclogen ME.

In addition to evaluating the emulsions, three different cover treatments were tested:

1) a chip seal;
2) a 1-inch HBP overlay; and
3) no cover.

The chip sealed section required the attention of maintenance the first summer and this section was eventually overlaid with HBP. The failure of this chip seal can be attributed to a combination of the high void content in the recycled mat, the fog coats which were applied (giving a very rich top 1/2" of mat), and the relatively high traffic volume for this type of treatment. Another district completed a cold-recycled project (with a chip seal) south of Limon on S.H. 71 the following summer. This project is performing well; however, it was constructed with warmer temperatures and lower traffic volumes.

The 1-inch HBP overlay performed well. Cracking in the recycled section was significantly lower than in the section which was not recycled. Influence cracking from the unrecycled shoulders appears to promote cracking in the recycled sections sooner, therefore it is recommended that the pavement section be cold-recycled full width.

The results from the lab tests performed on the cores were not indicative of how the pavement performed. With the high void contents and the low Hveem stabilities that are exhibited by the cores, rutting would be expected, however, there was no measurable rutting in any of the sections. It is felt that the high void content is a contributor in retarding reflective cracking in the recycled sections. Not recycling the shoulders on this project possibly promoted some of the early transverse cracking which appeared in the cold-recycled sections.

Milling up to 3 to 4 inches is common for this process and as stated by the contractor as being the most efficient depth of operation. Roadway surfaces with deep cracking potentially could benefit the most with deeper milling as it is felt that this process tends to retard cracking longer as opposed to the heater scarifier method which is limited to 1 to 1-1/2 inches in depth.

The section without a cover material performed poorly and extensive patching was required during the first winter. Stage construction which leaves the recycled material exposed through the winter is not recommended. With the high voids created by the cold-recycling process it is recommended that a wearing surface be used in conjunction with cold-recycling.

X. IMPLEMENTATION

This research study has shown cold-recycling to be an efficient and valuable method for rehabilitating asphalt pavements and retarding reflective cracking.

It is recommended that when scoping a project for rehabilitation that cold-recycling be given the same consideration as our standard methods. This is particularly important when dealing with severely cracked pavement with adequate bases.

REFERENCES

1. Pavement Profile Measurement Seminar Proceedings, Ft. Collins, Colo, October 5-8, 1987, Demonstration Project No. 72, Automated Pavement Data Collection Equipment, FHWA-DP-88-072-003, Volume 1, Data Seminar Overview, Appendix B.

2. Standard Specification for Transportation Materials and Method of Sampling and Testing, Part II Methods of Sampling and Testing, August 1986, AASHTO T246, p. 1040.

3. 1986 Cost Data, Colorado Department of Highways, January 1, 1986.

APPENDIX A

Specifications

June 20, 1986

REVISION OF SECTION 406
COLD BITUMINOUS PAVEMENT (RECYCLE)
COLORADO PROJECT NO. CX 04-0024-25

Section 406 is hereby added to the Standards Specifications for this project as follows:

DESCRIPTION

406.01

This work shall consist of pulverizing the existing bituminous surfacing, to the depth shown on the plans, mixing an emulsified binder agent and water (if required) with the pulverized bituminous surfacing, then spreading and compacting said mixture as shown on the plans and as provided herein, unless otherwise directed.

The Contractor shall furnish all equipment, tools, labor and any other appurtenances necessary to complete the work.

MATERIALS

406.02

The emulsified binder agent shall be High Float Emulsion, CSS-1H Modified, or Emulsified Recycling Agent of the type shown on the plans with the option, by the Department, to change one grade, at no increase in price. Any change in grade of binder agent shall be made only with the concurrence of the Engineer. The High Float Emulsion, CSS-1H Modified, or Emulsified Recycling Agent shall meet the requirements of Section 702 of the Standard Specifications as revised for this project.

The Cold Recycled Bituminous Material shall meet the following gradation requirements:

Sieve Size	% Passing
1-1/4"	100
1"	90-100

The Sealing Emulsion shall be High Float Emulsion (diluted), or other approved equal.

CONSTRUCTION REQUIREMENTS

406.03

The existing bituminous surfacing shall be cold recycled in a manner that does not disturb the underlying material in the existing roadway.

-continued-

REVISION OF SECTION 406
COLD BITUMINOUS PAVEMENT (RECYCLE)
COLORADO PROJECT NO. CX 04-0024-25

Recycling operations shall not be performed when the atmospheric temperature is below 50°F, or when the weather is foggy or rainy, or when weather conditions are such that proper mixing, spreading, and compacting of the recycled material cannot be accomplished.

When commencing recycling operations, the emulsified binder agent shall be applied to the pulverized bituminous material at the initial design rate determined by the Materials Laboratory, based on samples submitted prior to construction. The exact application rate of the emulsified binder agent will be determined, and may be varied as required by existing pavement conditions. An allowable tolerance of plus or minus 0.2 percent of the initial design rate or directed rate of application shall be maintained at all times.

The Contractor may add water to the pulverized material to facilitate uniform mixing with the emulsified binder agent. Water may be added prior to or concurrently with the emulsified asphalt, provided that this water does not cause any adverse effect on the emulsified binder agent.

The Contractor shall demonstrate his ability to obtain a minimum density of 95 percent of the laboratory specimen. The project Engineer may require a redemonstration of rolling capabilities when a change in the recycled material is observed, whenever a change in rolling equipment is made, or if densities are not being obtained with the rolling pattern being used.

After the recycled material has been spread and compacted, NO TRAFFIC (this includes Contractor's equipment) shall be permitted on the completed recycled bituminous material for at least two hours. The area shall then be opened to all traffic and the pavement shall be allowed to cure until the moisture content is reduced to 1% or less, by total weight of mix. Recycling operations shall cease early enough each day that both lanes are open to traffic prior to sunset.

After the moisture content of the recycled material has reached 1% or less, the sealing emulsion shall be applied to the surface at an approximate rate of 0.05 to 0.10 gallon per square yard.

Any damage to the completed recycled bituminous pavement shall be repaired by the Contractor at the Contractor's expense.

-continued-

REVISION OF SECTION 406
COLD BITUMINOUS PAVEMENT (RECYCLE)
COLORADO PROJECT NO. CX 04-0024-25

Any fillet of fine, pulverized material which forms adjacent to a vertical face shall be removed prior to spreading the recycled mix, except that such fillet adjacent to existing pavement which operation need not be removed. Vertical cuts in roadway shall not be left overnight.

EQUIPMENT

406.04

The Contractor shall furnish a self-propelled machine capable of pulverizing in-place bituminous materials to the depth shown on the plans, on one pass. Said machine shall have a minimum rotor cutting width of twelve feet, standard automatic depth controls and maintain a constant cutting depth. Said machine shall also incorporate screening and crushing capabilities to reduce or remove oversize particles prior to mixing with emulsion. Oversize particles shall be reduced to size by crushing.

The emulsified binder agent shall be applied through a separate mixing machine capable of mixing the pulverized bituminous material and the emulsified binder agent to a homogeneous mixture, and placing the mixture in a windrow. The method of depositing the mixed material in a windrow shall be such that segregation does not occur.

A positive displacement pump, capable of accurately metering the required quantity of emulsified binder agent at rates as low as 4 gal./min., shall be used to apply the emulsified binder agent to the pulverized bituminous material. Said pump shall be equipped with a positive interlock system which will permit addition of the emulsified binder agent only when the pulverized bituminous material is present in the mixing chamber and will automatically shut off when the material is not in the mixing chamber.

Each mixing machine shall be equipped with a meter capable of registering the rate of flow and total delivery of the emulsified binder agent introduced into the mixture.

Placing of the recycled bituminous material shall be accomplished with a self-propelled bituminous paver meeting the requirements of Subsection 401.10 as revised, except that heating of the screed will not be required. The bituminous recycled material shall be spread in one continuous pass, without segregation, to the lines and grades established.

-continued-

REVISION OF SECTION 406
COLD BITUMINOUS PAVEMENT (RECYCLE)
COLORADO PROJECT NO. CX 04-0024-25

When a pick-up machine is used to feed the windrow into the paver hopper, the pick-up machine shall be capable of picking up the entire windrow to the underlying materials.

The number, weight, and type of rollers shall be sufficient to obtain the required compaction while the mixture is in a workable condition except that the pneumatic roller(s) shall be 30 ton minimum weight.

Initial rolling shall be performed with the pneumatic roller(s) and continued until no displacement is observed. Final rolling as required to eliminate pneumatic tire marks and achieve required density shall be done by steel wheel roller(s), either in static or vibratory mode.

Rollers shall not be started or stopped on uncompacted recycled material. Rolling shall be accomplished so that starting and stopping will be on previously compacted recycled material or on existing pavement.

Any type of rolling that results in cracking, movement or other types of pavement distress shall be discontinued until the problem is resolved.

METHOD OF MEASUREMENT

406.05

In-place Cold Recycling of Bituminous Material shall be measured by the square yard.

BASIS OF PAYMENT

406.06

The accepted quantity of In-place Cold Recycling of Bituminous Material will be paid for at the contract unit price per Square Yard.

Payment will be made under:

PAY ITEM	PAY UNIT
Cold Bituminous Pavement (Recycle).	Square Yard

-continued-

REVISION OF SECTION 406
COLD BITUMINOUS PAVEMENT (RECYCLE)
COLORADO PROJECT NO. CX 04-0024-25

Bituminous materials will be measured and paid for as provided in Section 411.

Water used to dilute Emulsified Asphalt, High Float Emulsion, CSS-1H Modified, or Emulsified Recycling Agent will not be measured and paid for separately, but shall be included in the work.

APPENDIX B

Test Results

Division of Highways
State of Colorado
Form DOH 360 Rev. 11/88

Date Received 5- 5-89

Project No: Cold Recycling
Location: US 24, Colorado Springs
District # 2 Subaccount: 89001
Lab # B 127
Field Sample # 50901

- PROJECT PRODUCED HOT BITUMINOUS PAVEMENT -

Item 403 GRADING EX Core #7
Pit name: CONTRACTOR: Research

	Test Results	Job Mix	
% Moisture	.10	--	See sample #
% Asphalt	7.63	.00	
1	100.	0.	
3/4	100.	0.	
5/8	100.	0.	See DOH No. 43 dated 0- 0- 0
1/2	100.	0.	
3/8	100.	0.	
4	92.	0.	Sampling: CP 41 C
8	76.	0.	Extraction: T 164B
16	57.	0.	Gradation: T30
30	41.	0.	
50	28.	0.	
100	19.	0.	
200	13.8	.0	

TEST RESULTS:

Max Sp. Gr.	T209	2.320
Bulk Sp. Gr.	T166	1.956
% Voids	CPL 5105	15.7
Stability	CPL 5105	14.
Modulus	CPL 5110	329
Strength coefficient		.25
VMA (% voids in Agg)		30.6
% of VMA filled		49.
Dust / AC ratio		1.68

IMMERSION-COMPRESSION CPL 5104		LOTTMAN	CPL 5109
PSI Wet		7.	Wet D.T.St
PSI Dry		38.	Dry D.T.St
% Absorption		14.2	% Voids
% Swell		14.1	% Perm Vds
% Ret. Strength		18.	% T.S.Ret.

Date Reported 6/28/89

Dick Hines 757-9724
Flexible Pavement Engineer

Division of Highways
State of Colorado
Form DOH 360 Rev. 11/88

Date Received 5- 5-89

Project No: Cold Recycling
Location: US 24, Colorado Springs
District # 2 Subaccount: 89001
Lab # B 128
Field Sample # 50901

- PROJECT PRODUCED HOT BITUMINOUS PAVEMENT -

Item 403 GRADING E Core #7A
Pit name: CONTRACTOR: Research

	Test Results	Job Mix	
% Moisture	.14	--	See sample #
% Asphalt	7.93	.00	
1	100.	0.	
3/4	100.	0.	
5/8	100.	0.	See DOH No. 43 dated 0- 0- 0
1/2	100.	0.	
3/8	100.	0.	
4	93.	0.	Sampling: CP 41
8	76.	0.	Extraction: T 164B
16	57.	0.	Gradation: T30
30	42.	0.	
50	28.	0.	
100	19.	0.	
200	13.6	.0	

TEST RESULTS:

Max Sp. Gr. T209	2.323
Bulk Sp. Gr. T166	1.995
% Voids CPL 5105	14.1
Stability CPL 5105	14.
Modulus CPL 5110	338
Strength coefficient	.25
VMA (% voids in Agg)	29.9
% of VMA filled	53.
Dust / AC ratio	1.59

IMMERSION-COMPRESSION CPL 5104		LOTTMAN	CPL 5109
PSI Wet		9.	Wet D.T.St
PSI Dry		43.	Dry D.T.St
% Absorption		13.3	% Voids
% Swell		13.3	% Perm Vds
% Ret. Strength		20.	% T.S.Ret.

Date Reported 6/28/89

Dick Hines 757-9724
Flexible Pavement Engineer

Division of Highways
State of Colorado
Form DOH 360 Rev. 11/88

Date Received 5- 5-89

Project No: Cold Recycling
Location: US 24, Colorado Springs
District # 2 Subaccount: 89001
Lab # B 129
Field Sample # 50901

- PROJECT PRODUCED HOT BITUMINOUS PAVEMENT -

Item 403 GRADING EX Core #8
Pit name: CONTRACTOR: Research

	Test Results	Job Mix	
% Moisture	.20	--	See sample #
% Asphalt	7.14	.00	
1	100.	0.	
3/4	100.	0.	
5/8	100.	0.	See DOH No. 43 dated 0- 0- 0
1/2	100.	0.	
3/8	99.	0.	
4	91.	0.	Sampling: CP 41 C
8	75.	0.	Extraction: T 164B
16	56.	0.	Gradation: T30
30	37.	0.	
50	24.	0.	
100	16.	0.	
200	10.5	.0	

TEST RESULTS:

Max Sp. Gr.	T209	2.336
Bulk Sp. Gr.	T166	2.100
% Voids	CPL 5105	10.1
Stability	CPL 5105	20.
Modulus	CPL 5110	755
Strength coefficient		.30
VMA (% voids in Agg)		25.1
% of VMA filled		60.
Dust / AC ratio		1.37

IMMERSION-COMPRESSION CPL 5104
PSI Wet
PSI Dry
% Absorption
% Swell
% Ret. Strength

LOTTMAN	CPL 5109
21.	Wet D.T.St
68.	Dry D.T.St
9.6	% Voids
8.5	% Perm Vds
30.	% T.S.Ret.

Date Reported 6/28/89

Dick Hines 757-9724
Flexible Pavement Engineer

Division of Highways
State of Colorado
Form DOH 360 Rev. 11/88

Date Received 5- 5-89

Project No: Cold Recycling
Location: US 24, Colorado Springs
District # 2 Subaccount: 89001
Lab # B 130
Field Sample # 50901

- PROJECT PRODUCED HOT BITUMINOUS PAVEMENT -

Item 403 GRADING EX Core #9
Pit name: CONTRACTOR: Research

	Test Results	Job Mix	
% Moisture	.12	--	See sample #
% Asphalt	7.71	.00	
1	100.	0.	
3/4	100.	0.	
5/8	100.	0.	See DOH No. 43 dated 0- 0- 0
1/2	100.	0.	
3/8	100.	0.	
4	94.	0.	Sampling: CP 41 C
8	78.	0.	Extraction: T 164B
16	56.	0.	Gradation: T30
30	41.	0.	
50	25.	0.	
100	17.	0.	
200	12.4	.0	

TEST RESULTS:

Max Sp. Gr. T209	2.324
Bulk Sp. Gr. T166	2.002
% Voids CPL 5105	13.9
Stability CPL 5105	15.
Modulus CPL 5110	448
Strength coefficient	.25
VMA (% voids in Agg)	29.3
% of VMA filled	53.
Dust / AC ratio	1.49

IMMERSION-COMPRESSION CPL 5104		LOTTMAN	CPL 5109
PSI Wet		7.	Wet D.T.St
PSI Dry		51.	Dry D.T.St
% Absorption		13.6	% Voids
% Swell		13.4	% Perm Vds
% Ret. Strength		13.	% T.S.Ret.

Date Reported 6/28/89

Dick Hines 757-9724
Flexible Pavement Engineer

Division of Highways
State of Colorado
Form DOH 360 Rev. 11/88

Date Received 5- 5-89

Project No: Cold Recycling
Location: US 24, Colorado Springs
District # 2 Subaccount: 89001
Lab # B 131
Field Sample # 50901

- PROJECT PRODUCED HOT BITUMINOUS PAVEMENT -

Item 403 GRADING EX Core #9A
Pit name: CONTRACTOR: Research

	Test Results	Job Mix	
% Moisture	.06	—	See sample #
% Asphalt	7.72	.00	
1	100.	0.	
3/4	100.	0.	
5/8	100.	0.	See DOH No. 43 dated 0- 0- 0
1/2	100.	0.	
3/8	100.	0.	
4	93.	0.	Sampling: CP 41 C
8	76.	0.	Extraction: T 164B
16	55.	0.	Gradation: T30
30	39.	0.	
50	25.	0.	
100	17.	0.	
200	12.2	.0	

TEST RESULTS:

Max Sp. Gr. T209	2.327
Bulk Sp. Gr. T166	1.990
% Voids CPL 5105	14.5
Stability CPL 5105	14.
Modulus CPL 5110	407
Strength coefficient	.25
VMA (% voids in Agg)	29.8
% of VMA filled	51.
Dust / AC ratio	1.47

IMMERSION-COMPRESSION CPL 5104		LOTTMAN	CPL 5109
PSI Wet		7.	Wet D.T.St
PSI Dry		43.	Dry D.T.St
% Absorption		14.6	% Voids
% Swell		14.3	% Perm Vds
% Ret. Strength		15.	% T.S.Ret.

Date Reported 6/28/89

Dick Hines 757-9724
Flexible Pavement Engineer