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Final Report

PERFORMANCE OF COLORADO'S FIRST RUBBLIZATION PROJECT ON I 76 NEAR STERLING

Robert LaForce, P.E.
Yeh and Associates

January 2006

COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

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16. Abstract
This report documents the six-year performance of the Colorado DOT's first rubblization of PCCP project. The project is located on I 76 near Sterling, Colorado, and was selected to demonstrate the use of the resonant breaker and multi-head hammer methods of rubblization and the performance of the new HMA overlay. Edge drains were also installed and evaluated. Crack and seat technology was also to be constructed, but the equipment was unable to adequately fracture the interlocked reactive aggregate slabs, so the treatment was not used for construction.

Findings from this study include the following:

- Falling-weight deflectometer data from 2004 shows that the pavement has adequate structure to carry the traffic loading on I 76.
- The HMA pavement has no distresses associated with reflective cracking from the old concrete pavement and has not demonstrated any settlement, permanent deformation (rutting), or other distresses as a result of the rubblization processes.
- Both rubblization methods appear to have accomplished the required break-up of the old concrete pavement and both methods should be allowed on future projects.
- The tightly locked slabs resulting from reactive aggregate problems did not require any special requirements for rubblization. The standard fracturing required for each rubblization method was adequate to prevent damage to the new HMA overlay.
- The HMA pavement is performing similar to other newly constructed asphalt pavements and therefore any life cycle calculations should be treated the same as far as rehabilitation cycles or maintenance costs, except construction costs should include the cost of rubblization and the installation of edge drains. Maintenance costs will need to address edge drain maintenance in the future.
- The edge drains performed adequately in preventing moisture buildup under the pavement although only small amounts of moisture were encountered.
- Rubblization may provide CDOT with a cost competitive tool for the rehabilitation of old concrete pavements.

Implementation:

This report identifies costs and other data that could be used to incorporate rubblization as an option for the rehabilitation of concrete pavement into the Colorado DOT Pavement Design Manual

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Performance of Colorado's First Rubblization Project on I 76 near Sterling

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Prepared by
Robert F. LaForce
Yeh and Associates

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Colorado Department of Transportation
Research Branch
4201 East Arkansas Ave.
Denver, Colorado 80222

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EXECUTIVE SUMMARY

This report documents the six-year performance of the first rubblization of Portland cement concrete pavement (PCCP) project built by the Colorado Department of Transportation (CDOT). The project was selected to demonstrate the use of the resonant breaker and multi-head hammer methods of rubblization of a concrete pavement and the performance of the new hot mix asphalt (HMA) pavement overlay placed on the rubblized concrete.

The project is located on I 76 between Sterling and Iliff in Logan County. The existing pavement was originally constructed in 1967 and consisted of a two-inch emulsified asphalt treated base (Class 2) with eight inches of jointed plain concrete pavement (JPCP). Since initial construction, this section of pavement has had limited maintenance. In 1995, this section was overlaid with a 2-inch asphalt pavement, which was anticipated to be the bond breaker for the first phase of an unbonded Portland cement concrete pavement (PCCP) overlay.

When the decision was made to use the rubblization techniques on this project, the original plans were revised to incorporate removing the existing 2-inch asphalt overlay, rubblizing the concrete, and placing three two-inch lifts of HMA on the rubblized concrete.

The project used two methods of rubblizing the concrete pavement, the resonant breaker and the multi-head hammer method. Additionally, edge drains were installed to control subgrade moisture. Crack and seat technology was also to be constructed, but the equipment was unable to adequately fracture the interlocked reactive aggregate slabs, so that treatment was not used.

Since the technology was new to Colorado, a one-day seminar and open house was held to describe the pavement design and to demonstrate the rubblization processes. A field trip to the construction site was included.

In May, 2000, a Construction Report (Report No. CDOT-DTD-R-2000-4) was completed documenting the design, construction, and post-construction evaluation of this demonstration project. This final report will focus on the performance and cost of the rubblization project.

Findings from this study include the following:

- Falling weight deflectometer data from 2004 shows that the pavement has adequate structure to carry the traffic loading on I 76.

- The HMA pavement has no distresses associated with reflective cracking from the old concrete pavement and has not demonstrated any settlement, permanent deformation (rutting), or other distress as a result of the rubblization process.

- Both rubblization methods appear to have accomplished the required break-up of the old concrete pavement. Both methods should be allowed on future projects.

- This project contained reactive aggregate damaged concrete resulting in tightly locked-up slabs. No special requirements for rubblization were needed to address this pavement condition. The standard fracturing required for each rubblization method was adequate to prevent damage to the new HMA overlay.

- The HMA pavement is performing similar to other newly constructed asphalt pavements and therefore any life cycle calculations should be treated the same as far as rehabilitation cycles or maintenance costs except for the additional cost of maintaining edge drains. Construction costs should include the installation of edge drains and the cost of rubblization.

- Only small amounts of moisture were noted in the edge drains, which may be a result of project soil type, or a result of a 5-year drought in this area lasting from 1999 to 2004. The moisture probes worked from initial construction to late 2001, and enough data was gathered to document that the edge drains did prevent moisture from accumulating under the pavement

Based on the performance of this project, rubblization may provide CDOT with a cost-competitive tool in the rehabilitation of old concrete pavements.

IMPLEMENTATION STATEMENT

This report identifies costs and other data that could be used to incorporate rubblization as an option for the rehabilitation of a concrete pavement into the CDOT Pavement Design Manual.

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1.0 BACKGROUND

Colorado has approximately 1700 lane miles of Portland cement concrete pavement (PCCP) of which 33% is in need of rehabilitation. Typically, rehabilitation of PCCP consists of reconstruction, unbonded concrete overlays, or hot mix asphalt (HMA) overlays. Due to high growth rates and limited resources, many of these concrete pavements have served traffic far beyond their original design lives and many miles of these pavements need extensive rehabilitation in a cost-effective manner.

The design and construction of the Colorado Department of Transportation's (CDOT) first rubblization project is documented in the Construction Report "Interstate Asphalt Demonstration Project NH 0762-038 (Rubblization)" Report No. CDOT-DTD-R-2000-4[1]. The Construction Report documents, in detail, the design and construction of this project. An overview from the Construction Report is included in this report for continuity.

This report documents the follow-up evaluations and performance of this rubblization project and proposes methods to incorporate rubblization into the CDOT Pavement Design Manual.

2.0 PROJECT OVERVIEW

2.1 Project Selection

The project (NH 0762-038) selected for this study is located on I 76 between Sterling and Iliff, CO. in Logan County. (See Figure 1) The existing pavement on this section of I 76 was constructed in 1967 and consisted of a 2-inch emulsified asphalt treated base (Class 2) with 8 inches of jointed plain concrete pavement (JPCP). Since original construction, the pavement has had limited maintenance. In 1995, this section was overlaid with 2 inches of asphalt as a future bond breaker for an unbonded portland cement concrete (PCCP) overlay originally scheduled for 1999.

This project was selected to incorporate rubblization techniques for the rehabilitation of the concrete pavement. One of the reported benefits of rubblization is the ability for the work to be performed adjacent to existing traffic. In addition, the length of time traffic is in a two-way situation could be reduced when compared to a typical concrete overlay. However, because of structure work included in this project, a crossover detour was used to control traffic on this project, so no benefits from performing work next to live traffic were demonstrated or documented.

Another factor that led to the selection of this project was its three-mile length, which allowed for several evaluation sections. The project is located in both the eastbound and westbound directions of this four-lane facility. In 1999 this section of roadway had an average annual daily traffic volume of 5477 vehicles; 6% single unit trucks and 25% combination trucks. The 20-year flexible pavement design ESALs were 6,500,000.

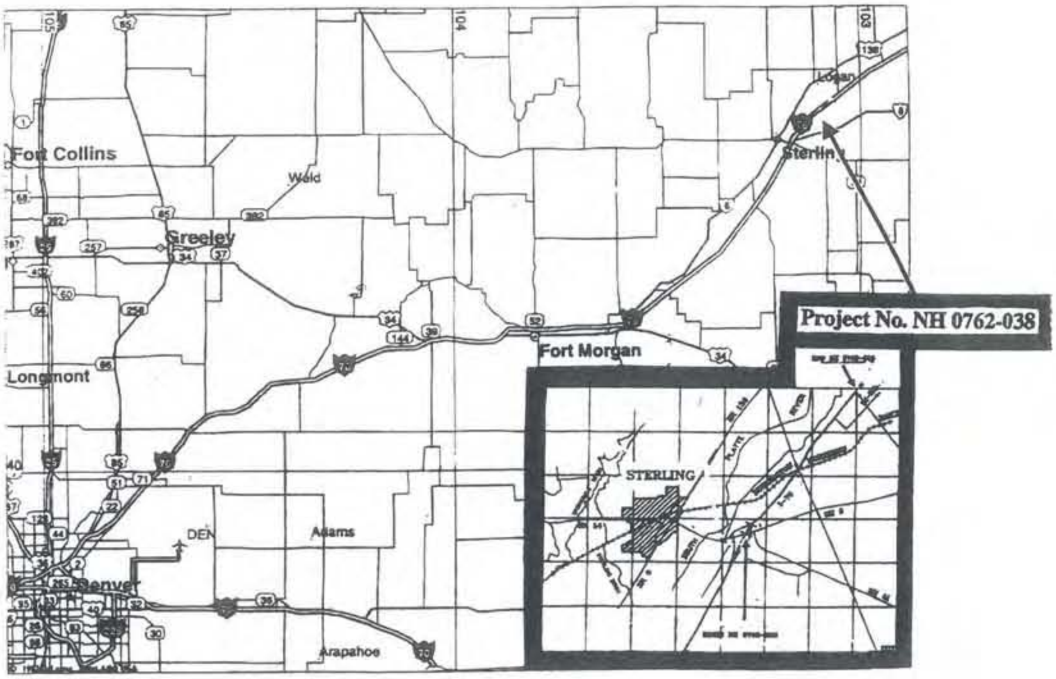

Figure 1. Location Map of Project NH 0762-038

2.2 Project Scope

Once the decision to incorporate rubblization techniques was finalized, the original plans were revised. The new plans dictated removing the existing 2-inch asphalt overlay and the milled material was to be used as shoulder material. The existing concrete was then originally scheduled to be rubblized using three processes, the resonant breaker, the multi-head hammer, and crack and seat.

One edge drain was to be placed on the outside of the concrete in each direction followed by the rubblization process, and three two-inch lifts of hot mix asphalt (HMA). Edge drains were to remove any existing moisture during the rubblization process and provide for drainage of subgrade moisture.

2.3 Seminar/Field Demonstration

As part of this research study, a one-day seminar to explain the pavement design and demonstrate the rubblization methods was held in Sterling, Colorado and at the project site on I 76. The seminar was hosted by CDOT and co-sponsored by the Asphalt Institute, the Federal Highway Administration, and the Colorado Asphalt Pavement Association. The purpose of the seminar was to provide technology transfer and insight into the rubblization processes.

Approximately 120 participants attended including representation from seven western state DOTs. The seminar portion of the program included discussions on overlay design of rubblized PCCP, rubblization and construction techniques, along with technical presentations from several rubblization experts at the national level. As part of the seminar, a field trip to the project site was held to observe the two rubblization processes as well as the crack and seat technology and equipment.

3.0 DESCRIPTION OF PROJECT

3.1 Initial Preparation

The existing 2-inch asphalt bond breaker overlay was removed with a rotomill. The rotomilled material was stockpiled adjacent to the shoulder to be used later for shouldering next to the new asphalt pavement.

The existing asphalt shoulders had extensive cracking and major deterioration. A Bomag CMI 650 Reclaimer was used to break the shoulder material to approximately a minus 1-inch size. This process was used to eliminate any voids present under the old shoulders that might have been caused by erosion over the years. The material was then compacted and graded prior to placement of the asphalt overlay. Figure 2 shows the condition of the asphalt shoulders before they were broken up with the Bomag as well as typical longitudinal cracking on the concrete pavement prior to rubblization.

Figure 2. Pre-construction Roadway and Shoulder Condition

3.2 Edge Drains

Edge drains used in conjunction with the rubblization are a recommended feature to control subgrade moisture. Preventing moisture buildup in the subgrade is important for the long-term performance of the pavement as well as during the construction phase. Although this section of highway was built on a permeable sandy subgrade, edge drains were installed as part of the roadway design in the event that there was any subgrade moisture. The edge drains were specified and installed according to CDOT M-Standard M 605-1. Figure 3 shows typical edge drain installation.

Figure 3. Typical Edge Drain Construction

3.3 Rubblization

The project plans called for three methods of rubblizing to be demonstrated on this project; the resonant breaker, the multi-head hammer, and the crack and seat method. However, due to extensive alkali-silica reactivity (ASR) deterioration and the tightly locked-up slabs in the old concrete pavement, the crack and seat method was unable to transmit enough energy to break through the slabs. The crack and seat process was not effective because it was unable to crack the pavement full depth and was discontinued from the remainder of the project. The area planned for the crack and seat method was split between the resonant breaker method and the multi-head hammer method. Figure 4 shows the location where each of the rubblization processes was used as well as the location of the evaluation sections.

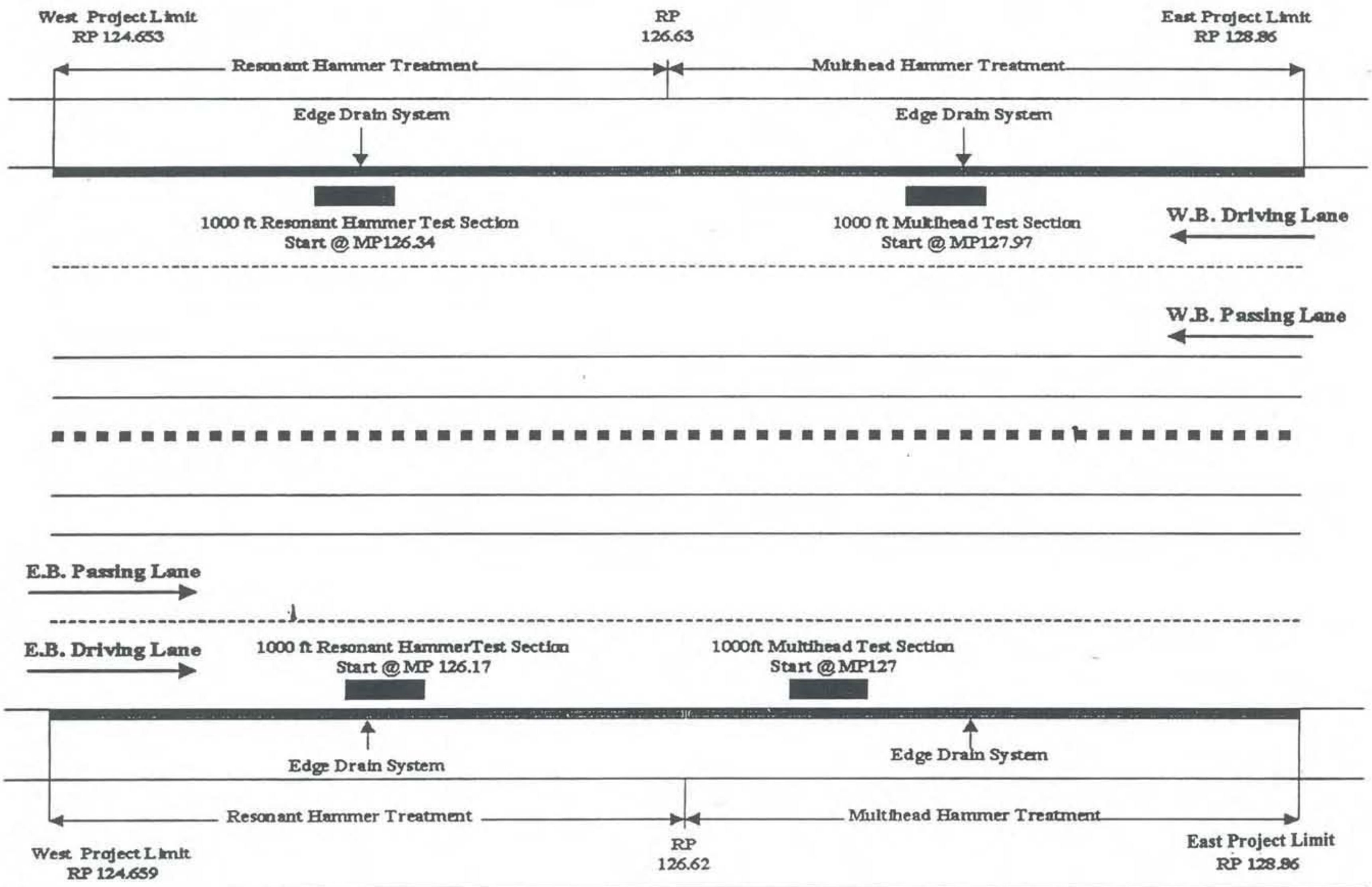

Figure 4. Evaluation Section Map

3.4 Resonant Breaker

Approximately half of each direction of I 76 was rubblized using the resonant breaker. A total of 39,361 square yards of concrete was rubblized using this method.

The specifications for this type of process required that the concrete pavement be broken up with a self-contained, self-propelled, resonant frequency pavement-breaking unit capable of producing low-amplitude 2,000-pound force blows at a rate not less than 44 cycles per second. The majority of rubblized concrete pieces should be 1 to 3 inches nominal size. (Specification in Appendix A of the Construction Report)

At the beginning of the rubblization operations, a 4-foot by 4-foot test section was excavated to visually inspect the size of the rubblized concrete and insure that the resonant breaker was producing the specified sizes.

Following the rubblization process and prior to placing the first HMA lift, a smooth drum 10-ton steel roller operating in the vibrating mode was used to seat the rubblized concrete.

The resonant breaker equipment and process can be seen in Figure 5. The equipment shown was provided by Resonant Machines, Inc. of Tulsa, Oklahoma.

3.5 Multi-Head Hammer

The remainder of the pavement was rubblized using the multi-head hammer. This section was approximately 1.4 miles in each direction; a total of 39,498 square yards of concrete.

With this process, the concrete pavement is broken up with a self-contained, self-propelled unit with hammers mounted laterally in pairs with half of the hammers in a forward row and the remainder diagonally offset in a rear row, so there is continuous breakage from side to side. The equipment was capable of rubblizing a 13-foot lane in a single pass. The existing concrete was broken into pieces ranging from sand size to pieces generally 3 inches or less in size in the top half of the concrete pavement, and 9 inches or less in the bottom half of the concrete pavement. (The specification is Appendix B of the Construction Report)

As with the resonant breaker sections, a 4-foot by 4-foot test section was excavated to visually inspect and verify that the multi-head hammer was producing the specified sizes. A steel vibratory roller fitted with “Z” pattern grid on the drum face operating in the vibratory mode was used to seat the rubblized pavement. Figure 6 and 7 shows the multi-head hammer and the Z-pattern roller. This equipment was provided by Antigo Construction Company of Antigo, Wisconsin.

Figure 5. Resonant Breaker

Figure 6. Multi-head Hammer

Figure 7. Z-Pattern Roller

3.6 Moisture Probes

Following the rubblizing, moisture probes were installed in the rubblized concrete to determine the effectiveness of the edge drains. Probes were placed at the interface of the rubblized concrete and the base. These probes measure a volumetric moisture content (VMC), and were calibrated to the soil type and compaction to measure soil moisture content.

Three locations within each research test section had moisture probes installed in the center of the driving lane, and one additional probe located one foot from the driving lane/shoulder joint. This location is near the edge drains and would sense any moisture draining through the rubblized concrete and edge drain system.

Additionally, a tipping rain gauge was installed in the immediate vicinity of the test sections. A data logger was used to capture hourly rainfall amounts and store data on a cassette recorder for later computer analysis. Data was downloaded from both the moisture probes and the rain gauge on a monthly basis.

3.7 Thickness Design

Since CDOT's experience with rubblization was limited, asphalt industry involvement with pavement design was solicited. The Asphalt Institute's recommendation was to place a minimum 6-inch HMA pavement on the rubblized concrete.

Using the "Guidelines for Use of HMA Overlays to Rehabilitate PCC Pavement,"[2] and using the following variables; H(pcc)=8", SN_{sb}=0 (the emulsified asphalt treated base was back to an A-3(0) sand), Heavy traffic, and Good Subgrade (A-3 to A-2-4 soil with resilient modulii of approximately 29,000 to 30,000 psi), and moisture at or near optimum) the calculation showed that an approximately 6-inch HMA pavement was required.

Before construction, a component analysis with similar inputs, using the AASHTO 1993 Darwin program, resulted in an overlay thickness of 2 inches. The Darwin component analysis is listed in Appendix A of the Construction Report (CDOT-DTD-R-2000-4).

Although the component analysis calculation resulted in a recommended HMA thickness of 2 inches, CDOT followed the Asphalt Institute's recommendation and a 6-inch HMA pavement was incorporated into the project plans. The original pavement design is listed in Appendix E of the Construction Report.

3.8 Construction

The project consisted of removing the existing 2 inches of asphalt pavement, installing edge drains, rubblizing the concrete pavement and reconditioning the shoulders, and then placing a full width 6-inch HMA pavement in three two-inch lifts.

Although the evaluation emphasis was on the rubblized concrete pavement and how it affects long-term performance of the asphalt pavement, the HMA mix design followed the current Superpave specifications for gradation, design gyrations, and binder selection. The design gyrations were 109, and the nominal ¾ inch mix contained either PG 70-34 or PG 76-28. The 98% reliability binder for this area is PG 70-28 using the LTPPBind Program and PG 70-34 using the more conservative SHRPBind Binder Selection Program.

The HMA for the project was produced using a Gencor continuous flow mixing plant with a capacity of 450 tons/hour. Four feed bins and a lime silo were used to blend the various components of the mix.

The HMA was delivered in both end dump and belly dump trucks. The haul time from the plant to the project was approximately 6 minutes and the mix temperature behind the paver was 149^{o}C (300^{o}F).

Paving was accomplished using a Caterpillar 950 rubber track paver with a 20-foot extendable screed. Paving widths were 15.5 feet for the passing lane and inside shoulder, 12.5 feet for the driving lane, and 11.0 feet for the outside shoulder. A 10-ton Ingersol Rand roller was used for breakdown and was kept right behind the paver. A 6-ton Hyster pneumatic (rubber tire) roller and a 10-ton Ingersol Rand roller were used for finish rolling. The roller pattern was established at the beginning of paving to accomplish the required 92-96% of maximum theoretical density.

4.0 PROJECT TESTING

4.1 Asphalt Mix Designs

Two different job mix formulas were used on this project. The first job mix formula utilized local crushed fines and sand. When the contractor began to experience problems obtaining density, a second mix design was developed. The new mix design used crushed fines and sand imported from the front range approximately 100 miles west of the project.

During the time between this project's award and construction, CDOT changed from the SHRPBind binder selection program to the LTPPBind binder selection program. The LTPPBind selection program 98% reliability binder for this project was PG 70-28 when traffic loading was considered. SHRPBind would have selected PG 70-34. The contractor also switched from PG 70-34 binder to PG 76-28. The PG 76-28 was chosen by the contractor because it was more readily available than the PG 70-28. Both of the above binders are polymer modified and in addition to meeting the Superpave requirements also met an elastic recovery test.

The contractor did not experience difficulty in achieving density using the new mix.

4.2 European "Torture" Test Results

In addition to standard CDOT mix testing such as Air Voids, Hveem Stability and Lottman, each mix used on this project was also tested using the French Rutting Tester to determine resistance to plastic flow rutting, and the Hamburg Wheel Tracking Device to determine resistance to moisture damage. A description of the European Equipment can be found in the report titled "Description of the Demonstration of European Testing Equipment for Hot Mix Asphalt Pavement."[3]

Results from the French Rut Tester are listed in Table A:

Table A - French Rut Tester Results (% Rut Depth after 30,000 cycles)

AC Source and Grade	Percent Rutting
Koch PG 70-34	3.76
Koch PG 76-28	2.50
Koch PG 76-28	4.00
Koch PG 76-28	2.55

A test temperature of 55°C (131°F) was used as determined by the climate in the project location.[4] Passing test results are considered a rutting depth less than or equal to 10% after 30,000 passes.

The results of the Hamburg Wheel Tracking Device are listed in Table B.

Table B – Hamburg Wheel Tracking Device Test Results

AC Source and Grade	Millimeters of Deformation after 20,000 passes
Koch PG 70-34	4.19
Koch PG 70-34	5.83
Koch PG 76-28	1.99
Koch PG 70-34	2.88
Koch PG 76-28	2.16

A test temperature of 55^{o}C (131^{o}F) was used as determined by the asphalt type.[5] Passing test results are considered deformation less than or equal to 10mm after 20,000 passes.

5.0 RESEARCH EVALUATIONS

Follow-up evaluations were planned to evaluate cracking, rutting, moisture monitoring, and falling weight deflectometer testing (FWD).

5.1 Rutting

Rutting measurements were taken during each annual evaluation. A six-foot straight edge was used to measure the rut depths in each wheel path of each lane. Measurements were taken at 50-foot intervals for the entire length of the 1000-foot test sections. Table C shows the average of the rut depths.

Table C - Summary of Rutting History
(Average Rut Measured mm.)

	WB Resonant Breaker					WB Multi-head Hammer			
	Driving Lane		Passing Lane			Driving Lane		Passing Lane	
	RWP	LWP	RWP	LWP		RWP	LWP	RWP	LWP
6-13-01	0.6	0.0	0.0	0.0		0.9	0.0	0.0	0.6
7-8-03	0.2	0.1	0.1	0.1		0.8	0.3	0.0	0.1
7-19-04	0.1	0.0	0.0	0.1		0.6	0.1	0.0	0.7

	EB Resonant Breaker					EB Multi-head Hammer			
	Driving Lane		Passing Lane			Driving Lane		Passing Lane	
	RWP	LWP	RWP	LWP		RWP	LWP	RWP	LWP
6-13-01	0.3	0.2	0.1	0.2		0.0	0.1	0.0	0.0
7-8-03	0.6	0.6	0.0	0.5		0.0	0.6	0.0	0.1
7-19-04	0.3	1.0	0.0	0.1		0.0	0.1	0.3	0.0

RWP = Right Wheel Path
LWP = Left Wheel Path

A review of the data in Table C shows a maximum of 1 mm of rutting has occurred since the original construction. These measurements show more of a variation in pavement texture than rut measurement. In the five years between construction and the final rut measurements in 2004, no significant rutting has occurred in this pavement.

The rutting performance of this pavement follows the predictions of rutting by the French Rut Tester.

5.2 Cracking

Cracking maps were updated with each annual evaluation to document the amount of cracking that occurred in the new asphalt pavements. This data was compared to the cracking condition in the concrete prior to construction.

Table D shows a summary of cracking since rubblization and placement of the new hot mix asphalt pavement.

Table D - Summary of Cracking History
(Linear cracking in feet)

	WB Resonant Breaker			WB Multi-head Hammer	
	Longitudinal	Transverse		Longitudinal	Transverse
6-13-01	0	10		27	11
7-8-03	64	10		110	11
7-19-04	106	10		168	11
Preconstruction Condition (Concrete Joints and Cracks)					
	WB Resonant Breaker			WB Multi-head Hammer	
	Longitudinal	Transverse		Longitudinal	Transverse
Cracking	1693	0		1524	125
Long. Joints	1000	0		1000	0
Trans. Joints	0	1563		0	1563

	EB Resonant Breaker			EB Multi-head Hammer	
	Longitudinal	Transverse		Longitudinal	Transverse
6-13-01	3	0		0	0
7-8-03	65	0		96	0
7-19-04	146	0		207	8
Preconstruction Condition (Concrete Joints and Cracks)					
	EB Resonant Breaker			EB Multi-head Hammer	
	Longitudinal	Transverse		Longitudinal	Transverse
Cracking	1395	125		568	0
Long. Joints	1000	0		1000	0
Trans. Joints	0	1563		0	1563

As can be seen in Table D, almost none of the cracking from the old concrete pavement has been noted in the new HMA pavement; especially noticeable is that a very small amount of transverse cracking has occurred.

After the 2001 evaluation, this asphalt pavement was identified as suffering from top-down cracking that was confirmed by coring later that year. Much of the current longitudinal cracking is attributed to top-down cracking. Figures 8 and 9 show the early crack and the core follow-up. As noted in the 2001 field notes, the crack was only 1/8 inch in depth at the time the core was taken (9/01).

Figure 8. Early Longitudinal Crack (Top-Down), 9/16/2001

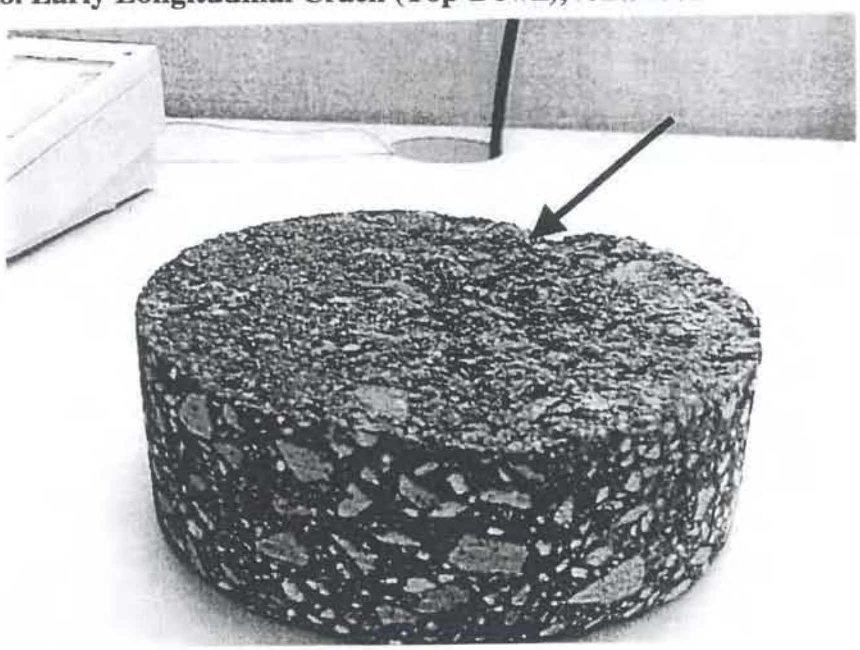

Figure 9. Core of Top-Down Cracking, 9/16/2001.

Another type of cracking that started to appear in 2001 and has progressed to the present is the opening of the longitudinal paving joints. A minor amount was noted during the 2001 evaluation in the multi-head section. Maintenance was asked at that time to fill the longitudinal joint cracks, as needed, following CDOT maintenance guidelines.

As a final note on cracking, the project was visited in September 2005. Figures 10 and 11 document the condition of the rubblization test sections. The top-down cracking has progressed in both directions with the eastbound lanes having more severe deterioration than the westbound lanes.

CDOT Maintenance forces have sealed most of the longitudinal cracking and the centerline of paving joint in both directions. The longitudinal joint between the shoulder and driving lane is now opened throughout the project length and will be sealed in the future.

Figure 10. Typical EB Condition (9/24/05)

Figure 11. Typical WB Condition (9/24/05)

The cracking history of the rubblization sections show that rubblization does work in preventing the concrete joints and cracks from reflecting through the new asphalt pavement.

5.3 Other Distresses

Maintenance forces have also spot sealed the wheel paths in some locations because the surface has started to ravel. Spot sealing has occurred in approximately 60% of the east-bound lanes and 25% of the westbound lanes. Figure 12 shows a close-up view of the surface texture of I 76 in the project area. The loss of fines was first noted in the 2002 field notes and has become a maintenance problem although this distress is not associated with the rubblization process. The loss of fines over time on this pavement supports the need for a wearing course relatively early in the life of a new pavement to protect the structural lower layers, and extend the useful life of a pavement. Both mixes used on this project passed all of the Lottman tests as well as the Hamburg Wheel Tracking tests.

Figure 12. Raveled Pavement Surface

5.4 Falling Weight Deflectometer Testing and Analysis (FWD)

In the construction report (Report No. CDOT-DTD-R-2000-4), FWD data and analysis was presented for the preconstruction condition. The FWD measurements showed that the load transfer of the old concrete slabs was surprisingly good. Load transfer ranged from 83 to a high of 95%, which indicates a very good load transfer mechanism in the reactive aggregate damaged concrete. Most of the project had load transfer between 83 and 89%. After rubblization, the FWD deflections showed that load transfer ranged from 64 to 69% with the exception of one multi-head hammer section with a load transfer of 45%. As noted in the Construction Report, this section received two passes using the multi-head hammer. Load transfer measurements of less than 50% are indicative of complete fracture.

At the time of construction, one of the aspects to be determined was if less than 50% load transfer was needed for a successful rubblization project. Based on the cracking histories shown in Table D, there is no significant difference in the amount of cracking that occurred in any of the test sections. Additionally, at this point in time, the only distresses that have appeared are either asphalt mix related or construction related (top-down cracking), and are not associated with the rubblization process.

FWD measurements were taken during construction for each layer of the new pavement, rubblized PCCP, and after1st lift, 2nd lift, and top lift of HMA and the subgrade resilient modulus and effective pavement modulus was back-calculated using the Darwin Pavement Design Program. This method was again used with the 2004 FWD data and the subgrade resilient modulus and effective pavement modulus were back-calculated for each test section and compared to the 1999 values. Table E shows the back-calculated data for 1999 and 2004 for each test section.

Table E - Comparative FWD Data

	EB Resonant Breaker	EB Multi-head Hammer	WB Resonant Breaker	WB Multi-head Hammer
1999 Subgrade Resilient Modulus	16,374	18,224	19,991	17,354
2004 Subgrade Resilient Modulus	16,373	19,672	19,776	16,525
1999 Effective Pavement Modulus	86,926	61,481	79,665	99,195
2004 Effective Pavement Modulus	318,158	293,381	251,458	248,651

As can be seen in Table E, the subgrade modulus has not significantly changed, nor are the two directions much different as far as base strength is concerned.

The type of rubblization equipment (method of rubblization) does not seem to affect the subgrade or pavement modulus.

As shown in Table E, during the five years since construction, the calculated effective pavement modulus has increased dramatically and the total deflection has been reduced from 15 to 19 mils to 7-8 mils. This increase in effective pavement modulus (stiffening of the pavement section) is believed to be caused by a combination of cementing of the rubblized concrete, and also stiffening of the asphalt pavement. Regardless of the reason, both eastbound sections have approximately the same Effective Pavement Modulus, and both westbound lanes have approximately the same Effective Pavement Modulus, indicating that the type of rubblization equipment did not make a significant difference in the effectiveness of rubblization. The westbound Effective Pavement Modulus is approximately 20% lower that the eastbound lanes.

5.5 Performance of Rubblization Methods

As noted in the Construction Report, the crack and seat method was not used on this project because the equipment could not completely fracture concrete slabs damaged by reactive aggregate.

The resonant breaker and multi-head hammer split the project area and each method was used to rubblize approximately half of the project. The fracturing size requirements were not the same for the two methods. The resonant breaker was required to fracture the existing concrete: “into pieces ranging from sand size to pieces generally 6 inches or less in size. No individual pieces shall exceed 8 inches in any dimension. The majority of rubblized concrete volume shall be nominal 1 to 3 inches in size.” The multi-head hammer was required to fracture the existing concrete: “into pieces ranging from sand size to pieces generally 3 inches or less in size in the top half of the concrete pavement and 9 inches or less in the bottom half of the concrete pavement. No individual pieces shall exceed 9 inches in any dimension.” Test pits were used to insure that the proper amount and size of fractured concrete was produced. Each method did produce the specified product on the roadway.

As noted in the cracking portion of this report, no reflection cracking from the old concrete was noted in the five years since construction, and no base-related distresses have been seen on this project.

Based on this performance, both methods produced the desired product, a fractured concrete pavement which did not fail as a base, and which did not promote reflective cracking. Both methods should be allowed on future rubblization projects.

5.6 Performance of Edge Drains

Moisture measurements were taken by the monitoring system with interruptions for winter from original construction well into 2001. As mentioned in the Construction Report and the 2001 annual evaluation, there is a tendency for somewhat higher moisture levels at the mid-lane location with progressively lower values with increasing depth. The moisture values were relatively constant after initial construction, and the values tend to confirm that moisture is migrating from the lane interior toward the edge drain, hence the drainage system is working. Visual observation of the drain outlets showed that only after intense rainfall could the presence of water be observed at the drain outlets. Moisture levels in the subgrade of this project were relatively low throughout the evaluation period.

There has been a great deal of discussion concerning the need for edge drains in the relatively dry climate found in eastern Colorado. This is especially true in locations like this one on I 76 where the underlying soils were mostly A-3(0) sands. If the soils below the old concrete pavement are not free draining, there exists a potential that the rubblized concrete will hold water and result in pumping and other base problems. Because of these potential subgrade moisture issues, edge drains should be included unless the subgrade soils can be shown to be free draining under normal rainfall and snow conditions.

6.0 PROJECT COSTS

6.1 Construction Costs

The Construction Report documented a comparison between the Engineer’s Estimate for a rehabilitation using a bond breaker and rubblization with the construction of this asphalt pavement. “The original Engineer’s Estimate for the roadway bid items for concrete pavement with a bond breaker was $5,675,167.20 (30-year design). The Engineer’s estimate for the roadway bid items for HMA and rubblization was $4,973,901.20 (20-year design).” The difference between the two estimates of construction costs was 14%. However, as noted in the Construction Report, the performance of this project will help establish the basis for alternate life cycle costs for the two rehabilitation methods.

6.2 Life Cycle Costs

In order to compare costs of the two types of rehabilitation and reconstruction in a life cycle cost, the major items to be included are:

Concrete Pavement Option:

Bond Breaker Overlay (2”)

New Concrete Pavement (10”)

Annual Maintenance Costs (Following CDOT Guidelines for PCCP Pavements)

Periodic Rehabilitation (Following CDOT Guidelines for PCCP Pavements)

PCCP Option - Current CDOT costs will be used for the bond breaker overlay and new concrete pavement. The values from the CDOT Pavement Design manual will be used for annual maintenance costs of PCCP pavement and periodic rehabilitation treatments.

Asphalt Pavement Option:

Rubblization (Mainline)

Shoulder Treatment (Pulverization if HMA, Rubblization if PCCP)

Edge Drains (one per direction)

New HMA Pavement

Annual Maintenance Costs (Following CDOT Guidelines for HMA Pavements)

Periodic Rehabilitation (Following CDOT Guidelines for HMA Pavements)

HMA Option – Current CDOT costs will be used for pulverization of the asphalt shoulders and the new HMA pavement. The values from the CDOT Pavement Design Manual will be used for annual maintenance and costs of periodic rehabilitation treatments. Edge drain installation and rubbization costs will be taken either from this project, or the latest costs from the recent rubblization project in Castle Rock. For annual maintenance costs of edge drains, data from the "NCHRP Synthesis of Highway Practice 285, Maintenance of Edge Drains"[6] will be used. Chapter 6 of that synthesis gives typical annual costs for the maintenance of edge drains per length of roadway in man-hours, as well as costs of cleaning etc. The following Table 5 from that report is recreated here as Table F.

In order to run an example of a life cycle cost using the above elements, a cost for each item needs to be established.

Table F – Maintenance Costs for Edge Drains
(Including Mobilization and Reporting)

Maintenance Activity	Frequency	Time Required hr/mi (hr/km)of road	Man Hours * hr/mi (h/km) of road
Visual Inspection (1-person crew)	Twice/year	3.2 (2)	6.4 (4)
Outlet and ditch line cleaning (3-person crew)	Once/7 years based on visual inspection	28.8 (18)	12.8 (8)
Video inspection (2-person crew)	Once/7 years	44.8 (28)	12.8 (8)
Flushing (2-person crew)	Once/7 years	28.8 (18)	8.0 (5)
Total		-	40 (25)

*Annual cost = column 1 X column 2 X column 3

Since most of Colorado has dry climate, the estimate will assume that the last two items, video inspection and flushing, would be done as part of the 10-year rehabilitation, so those costs will be added to the 10-year rehabilitation cost.

The first two items above, would be done by CDOT maintenance, and will become part of the annual maintenance costs of this treatment. Using column 4 in the above table , the man-hours per kilometer are converted to man-hours per lane mile as follows: 12 hrs/lane-km X 1.6 km /mile = 19.2 hours/lane-mile. CDOT maintenance man-hours vary from $32 to $34/hour, so using a maintenance man-hour cost of $33/hour, the cost of maintaining edge drains will increase by $634/year/lane mile of edge drain.

Video inspection and flushing require 42 man-hours per kilometer when done at 7-year intervals, so reducing the frequency to once per 10 years decreases the annual cost to: 42 hours/km X 1.6 km/mile = 67.2 hours each 10 years, so each 10-year rehabilitation will be increased by a cost of $33/hour X 67.2 hours = $2,218.

Additionally, a pavement design for each option addressing the same traffic loading, subgrade support condition, and same time frame would be required.

For this example, a section of I 76 near Brush was used to provide traffic information. Traffic volumes and design ESALs were obtained from the CDOT Traffic Website for the 20-year flexible design and the 30-year rigid pavement design. The same site was also used to obtain volumes for input into the user cost program for the various rehabilitation treatments.

Appendix A shows the complete life cycle inputs along with the sources of the costs used in the life cycle cost comparison.

Appendix B shows the pavement design and the complete DARWin output for a 40-year life cycle cost for a concrete pavement using a bond breaker overlay.

Appendix C shows a pavement design and the complete DARWin output for a 40 life cycle cost for a Hot Mix Asphalt Pavement using rubblization and overlay for rehabilitation.

The DARWin calculations yielded the following for construction and 40-year life cycle costs:

Table G - Initial Construction and Life Cycle Costs

	PCCP w/Bond Breaker	HMA w/ Rubblization
Initial Construction Cost	$6,196,062	$4,057,417
Net Present Value of 40-Year Life Cycle Cost	$6,513,130	$6,073,435

As can be seen in the above table, the initial construction cost of the rubblization with HMA option is 65% of the cost of the PCCP with bond breaker option and the 40-year life cycle costs show that the rubblization option is approximately 7% lower that the PCCP option.

The CDOT Pavement Design Manual states that two options within 10% on a 40-year live cycle cost analysis are considered to be of equal cost because of the unknowns in a 40-year analysis. These two options should be considered very cost competitive.

7.0 SUMMARY AND CONCLUSIONS

As noted in the Executive Summary, rubblization of PCCP followed by an appropriate thickness of hot mix asphalt will provide another alternative for consideration by CDOT in the rehabilitation of concrete pavements.

Both the resonant breaker and multi-head hammer method of breaking the concrete pavement worked, so both methods should be allowed on any future rubblization project.

Edge drains were shown to be effective in preventing moisture from building up under the rubblized concrete and should be used in conjunction with rubblization unless the subgrade below the concrete can be shown to be free draining.

Information to incorporate the cost of rubblization into a life cycle cost comparison with other treatments has been supplied and demonstrated in this report.

This pavement experienced extensive top-down and construction joint cracking. As noted earlier, these distresses are not related to the rubblization process. Colorado DOT standard specifications have been subsequently changed to help prevent the occurrence of these distresses.

8.0 IMPLEMENTATION

The use of rubblization and overlay with hot mix asphalt should be incorporated into the CDOT Pavement Design Manual so that the method can be compared to other rehabilitation methods.

9.0 REFERENCES

Harmelink, Donna, Hutter, Werner, and Vickers, Jeff., "Interstate Asphalt Demonstration Project, NH 0762-038 (Rubblization) Construction Report." Colorado Department of Transportation, Report No. CDOT-DTD-R-2000-4, May 2000.

National Asphalt Pavement Association, "Guidelines for Use of HMA Overlays to Rehabilitate PCC Pavement." Information Series 117, Prepared by Pavement Consultancy Services, 1994.

Aschenbrener, Tim and Stuart, Kevin, "Description of the Demonstration of European Testing Equipment for Hot Mix Asphalt Pavement," Colorado Department of Transportation, CDOT-DTD-R-92-10, October 1992.

Aschenbrener, Timothy, "Comparison of the Results Obtained from the French Rutting Tester with Pavements of Known Field Performance," Colorado Department of Transportation, CDOT-DTD-R-92-11, October 1992.

Aschenbrener, Timothy, and Currier, Gray, "Influences of Testing Variables on the Results from the Hamburg Wheel-Tracking Device," Colorado Department of Transportation, CDOT-DTD-R-93-22, December 1993.

National Cooperative Highway Research Program, "Maintenance of Highway Edgedrains" Synthesis of Highway Practice 285, Prepared by Barry R. Christopher, Ph.D., P.E., 2000.

APPENDIX A

Appendix A

Worksheet for Quantities comparing Rubblization-HMA and PCCP

Cost Comparison is for Three Miles of Four Lane Interstate with a Crossover Detour

Construction Items Used:

PCCP Option	Item Cost	Cost Source	
Bond Breaker Overlay	$41.75/ton	1	PG 64-22
New PCCP Pavement	$27.45/yd2	7	PCCP system
Annual Maintenance Costs	$150/lane-mile	3	
Periodic Rehabilitation			
(grind driving lanes & replace	$3.27/yd2	4	
0.5% of slabs @ 22 years)	$86/yd2	4	

HMA Option

Rubblization	$2.07/yd2	5	
Shoulder Treatment (Pulver.)	$1.40/yd2	2	
Edge Drains (one per direction)	$8.35/lin ft	5	
New HMA Pavement (PMA)			
6 inch	$46.50/ton	1	PMA
Annual Maintenance Costs	$1300/lane-mile	3	
Annual Edge Drain Maint.	$634/lane-mile	6	

Periodic Rehabilitation
(two inch overlay and edge drain maintenance @
10, 20, and 30 years with planing at 20 and 30 years)

2" Overlay	$46.5/ton	1	PMA
2" planing	$2.00/yd2		
Edge Drain Maintenance,			
video inspect. and flushing	$2,218/drain-mile	6	

Appendix A

Worksheet for Quantities comparing Rubblization-HMA and PCCP - continued

Cost Comparison is for Three Miles of Four Lane Interstate with a Crossover Detour

Cost Sources

1 - Project Number: STA 0712-012, Subaccount: 14712, Awarded: 01/20/05
2 - Project Number: IM 0761-190, Subaccount: 14838, Awarded: 06/09/05
3 - CDOT Pavement Design Manual
4 - Project Number: IM 0701-169, Subaccount: 15028, Awarded: 05/12/05
5 - Founders Parkway - Castle Rock Project - 04/05
6 - Edge Drain Maintenance from CDOT Man-hour cost
7 - Project Number: HB 0405-024, Subaccount: 12490, Awarded: 05/05/05

PCCP Option Quantities

2 inch Bond Breaker Overlay

133760 yd2 X 220lbs/yd2 X 1 ton/2000 lbs = 14,713.6 tons HMA	14713.6 tons
one direction =	**7356.8 tons**

Full Pavement Width (New PCCP)

3 miles X 38ft/3 ft/yd X 1760 yd/mi X 2directions = 133,759.99 =>	133760 yd2
one direction =	**66880 yd2**

Travel Lanes (50% driving lane Diamond Grinding Quantity)

3 mi X 24ft/3 ft/yd X 1760 yd/mi X 2 dir X 50% = 42240 yd2 =>	42240 yd2
one direction =	**21120 yd2**

Travel Lanes (Slab Replacement Quantity 0.5% of Driving Lanes)

3 miles X 24ft/3 ft/yd X 1760 yd/mi X 2dir X 0.5% = 422.2 yd2 =>	422.4 yd2
one direction =	**211.2 yd2**

Annual Maintenance

$150/lane mile X 3 miles X 4 lanes/mile =	$1,800
one direction =	$900

Appendix A

Worksheet for Quantities comparing Rubblization-HMA and PCCP - continued

Cost Comparison is for Three Miles of Four Lane Interstate with a Crossover Detour

Rubblization + HMA Option Quantities

Full Pavement Width (New HMA Pavement)

3 miles X 38ft/3 ft/yd X 1760 yd/mi X 2directions = 133,759.99 =>	133760 yd2
one direction =	**66880 yd2**

6 inch HMA Pavement

133760 yd2 X 660lbs/yd2 X 1 ton/2000 lbs = 44,140.8 tons HMA	44140.8 tons
one direction =	**22070.4 tons**

Travel Lanes (Rubblization Quantity)

3 mi X 24ft/3 ft/yd X 1760 yd/mi X 2 dir = 84480 yd2 =>	84480 yd2
one direction =	**42240 yd2**

Shoulders (Pulverization)

3 mi X (4+10)ft/3 ft/yd X 1760 yd/mi X 2 dir = 49280 yd2 =>	49280 yd2
one direction =	**24640 yd2**

Edge Drain Quantity

3 miles X 5280 ft/mile X 2 directions = 31680 ft	31680 ft
one direction =	**15840 ft**

Periodic Rehabilitation (2-inch PMA Overlay at 10, 20, and 30 Years)

133760 yd2 X 220lbs/yd2 X 1 ton/2000 lbs = 14,713.6 tons HMA	14713.6 tons
one direction =	**7356.8 tons**

Annual Maintenance (Including Edge Drains)

$1,300 /lane mile X 3 miles X 4 lanes =	$15,600	one direction =	$7,800
$634/lane mile X 3 miles X 2 directions =	$3,804	one direction =	$1,902
Project Total =	$19,404	one direction =	$9,702

$19,404 / 12 lane-miles = $1,617 /lane-mile

APPENDIX B

Appendix B

Life Cycle Cost
Portland Cement Concrete Pavement

Life Cycle Cost Calculations

Darwin Pavement Design Sheet

User Cost Calculations
- Construction - Cross-over Traffic Control
- Rehabilitation Cycles - Single Lane Closure 6AM to 8 PM

CDOT Traffic
- 30-Year ESALs for Thickness Design
- 22 Year Volume for User Cost Calculations

1993 AASHTO Pavement Design

DARWin Pavement Design and Analysis System

A Proprietary AASHTOWare
Computer Software Product

Life Cycle Cost Module

PCC Pavement 40 years

Life Cycle Cost Data

Summary

Analysis Period	40 years
Project Length	3 mi
Discount Rate	4 %
Number of Lanes in One Direction	2
Type of Roadway	Divided

Total Costs -- Using NPV on a basis of total costs for both directions

Initial Construction Cost	$6,196,062
Rehabilitation Cost	$317,069
Salvage Value	$0
Total Cost	$6,513,130

Initial Construction

PCC Paving

Construction Year	2005
Performance Period	22 years

Cost Information -- Using NPV on a basis of total costs for both directions

Information Type	Source	Costs at Year of Construction (One Direction)	Net Costs
Construction	DARWin Calculated	$3,085,404.58	$6,170,809.16
Maintenance	DARWin Calculated	$12,626.24	$25,252.49
Total	-	$3,098,030.82	$6,196,061.65

Rehabilitation #1

0.25-inch Diamond Grinding & 0.5% Slab Replacement

Rehabilitation Year	2027
Performance Period	18 years

Cost Information -- Using NPV on a basis of total costs for both directions

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$364,764.43	$307,828.63
Maintenance	DARWin Calculated	$10,949.10	$9,240.07
Total	-	$375,713.53	$317,068.70

Salvage Values

Salvage Year 2045

Cost Information -- Using NPV on a basis of total costs for both directions

Phase	Description	Source	Salvage Value	Net Value
Initial Construction	-	DARWin Calculated	$0.00	$0.00
Rehabilitation #1	-	DARWin Calculated	$0.00	$0.00

Initial Construction Maintenance Costs

Year Maintenance Costs Begin	2006
Annual Maintenance Costs	$150.00 per lane mi
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $12,626.24

Rehabilitation #1 Maintenance Costs

Year Maintenance Costs Begin	2028
Annual Maintenance Costs	$150.00 per lane mi
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $10,949.10

Initial Construction Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
10% Design Engineering	N.A.	NA	10%	$1,866,700.00	0	$186,670.00
18.1% Construction Engineering	N.A.	NA	lump sum	$337,872.70	1	$337,872.70
15% Traffic Control	N.A.	NA	15%	$1,866,700.00	0	$280,005.00
Concrete Pavement (10.0"/250mm)	T.L.	1	sq yd	$27.45	66,880	$1,835,856.00
Net User Cost	N.A.	NA	lump sum	$137,156.42	1	$137,156.42
Overlay of Existing	T.L.	2	ton	$41.75	7,374	$307,844.46

Non Discounted Costs (One Direction)

Traffic Lane	$2,143,700.46
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$941,704.12

Total Non Discounted Cost (One Direction) $3,085,404.58

Rehabilitation #1 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
1% Slab Replacement	T.L.	1	lump sum	$18,163.20	1	$18,163.20
Diamond Grinding	T.L.	1	sq yd	$3.27	66,880	$218,697.60
10% Design Engineering	N.A.	NA	10%	$156,605.00	0	$15,660.50
18.1% Construction Engineering	N.A.	NA	lump sum	$28,345.51	1	$28,345.51
15% Traffic Control	N.A.	NA	15%	$156,605.00	0	$23,490.75
Net User Cost	N.A.	NA	lump sum	$60,406.87	1	$60,406.87

Non Discounted Costs (One Direction)

Traffic Lane	$236,860.80
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$127,903.63
Total Non Discounted Cost (One Direction)	$364,764.43

Salvage Value Pay Items for Initial Construction

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost

Non Discounted Costs (One Direction)

Traffic Lane	$0.00
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00
Total Non Discounted Cost (One Direction)	$0.00

Salvage Value Pay Items for Rehabilitation #1

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost

Non Discounted Costs (One Direction)

Traffic Lane	$0.00
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00
Total Non Discounted Cost (One Direction)	$0.00

Initial Construction -- Traffic Lane Dimensions

Layer	Material Description	Width (ft)	Thickness (in)
1	Concrete Pavement (10.0"/250mm)	38	10
2	BOND BREAKER OVERLAY	38	2

Initial Construction -- Inner Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Initial Construction -- Outer Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Rehabilitation #1 -- Traffic Lane Dimensions

Layer	Material Description	Width (ft)	Thickness (in)
1	1% Slab Replacement	38	10
2	Diamond Grinding	24	0.25

Milling Thickness - in

Rehabilitation #1 -- Inner Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Milling Thickness - in

Rehabilitation #1 -- Outer Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Milling Thickness - in

1993 AASHTO Pavement Design

DARWin Pavement Design and Analysis System

A Proprietary AASHTOWare
Computer Software Product

Rigid Structural Design Module

Portland Cement Concrete Pavement (30 years)

Rigid Structural Design

Pavement Type	JPCP
18-kip ESALs Over Initial Performance Period	26,069,784
Initial Serviceability	4.5
Terminal Serviceability	2.5
28-day Mean PCC Modulus of Rupture	650 psi
28-day Mean Elastic Modulus of Slab	3,400,000 psi
Mean Effective k-value	800 psi/in
Reliability Level	95 %
Overall Standard Deviation	0.34
Load Transfer Coefficient, J	2.8
Overall Drainage Coefficient, Cd	1
Calculated Design Thickness	10.02 in + 0.25" = 10.27 => USE 10.5 inches

Effective Modulus of Subgrade Reaction

Period	Description	Roadbed Soil Resilient Modulus (psi)	Base Elastic Modulus (psi)
1	base	3,026	15,000

Base Type	Class 6
Base Thickness	6 in
Depth to Bedrock	10 ft
Projected Slab Thickness	10 in
Loss of Support Category	1
Effective Modulus of Subgrade Reaction	64 psi/in

CDOT REPORT - Summary Input and Output for the Crossover Strategy

	INPUT DATA		
Project Name	Brush		
Freeway Name	I76		
Input File			
Project Start Date			
Project End Date			
Design Speed	75 mph		
Speed Limit	75 mph		
Workzone Speed Limit	55 mph		
Grade	2.0 %		
Work Zone Length	3.00 miles		
Functional Class	Rural Interstate (Weekday)		
INBOUND		**OUTBOUND**	
Total Number of Lanes	2	**Total Number of Lanes**	2
Number of Open Lanes	1	**Number of Open Lanes**	1
Number of Temporary Lanes	0	**Number of Temporary Lanes**	0
AADT	4200	**AADT**	4200
Percentage of Single Unit Trucks	4.0 %	**Single Unit Trucks(%)**	4.0 %
Percentage of Combination Trucks	27.0 %	**CombinationTrucks(%)**	27.0 %
	OUTPUT SUMMARY		
	ADDITIONAL USER COST DUE TO WORKZONE		
TYPE OF WORK	**INBOUND COST**	**OUTBOUND COST**	**DURATION**
403-HBP (Asphalt) <= 1.0 inch	$22,891.56	$22,891.56	10
412-Concrete Pavement <= 10.0 inc	$114,264.86	$114,264.86	50
TOTAL ADDL. USER COST	$137,156.42	$137,156.42	60
TOTAL USER COST FOR NORMAL CONDITION (WITH NO WORKZONE)			
FOR A DURATION OF 60 DAYS : INBOUND = $677,485.65 OUTBOUND = $677,485.65			
Disclaimer:			
The values presented in this program are intended to provide guidelines only.			
Engineering judgement must be applied to use these values.			
No one but the user can assure that these results are properly applied.			

2006 Volume
Cross Over Lane Closure
24 Hour Closure

CDOT REPORT - Summary Input and Output for the Single Lane Closure Strategy

	INPUT DATA	
Project Name	Brush	
Freeway Name	I 76	
Input Filename		
Project Start Date		
Project End Date		
Design Speed	75 mph	
Speed Limit	75 mph	
Workzone Speed Limit	55 mph	
Grade	2.0 %	
Work Zone Length	3.00 miles	
Total Number of Lanes	2	
Number of Open Lanes	1	
Number of Temporary Lanes	0	
AADT, Directional	6317	
Percentage of Single Unit Trucks	4.0 %	
Percentage of Combination Trucks	27.0 %	
Functional Class	Rural Interstate (Weekday)	
	OUTPUT SUMMARY	
TYPE OF WORK	**ADDITIONAL USER COST** **DUE TO WORKZONE**	**DURATION**
202-Removal of Concrete (Diamond Grinding)	$44,818.65	17
412-Routing & Sealing PCCP Cracks	$15,588.22	6
TOTAL ADDL. USER COST	$60,406.87	23
TOTAL USER COST FOR NORMAL CONDITION (WITH NO WORKZONE)		
FOR A DURATION OF 23 DAYS = $290,233.39		
Disclaimer:		
The values presented in this program are intended to provide guidelines only.		
Engineering judgement must be applied to use these values.		
No one but the user can assure that these results are properly applied.		

2028 Volume
Single Lane Closure
6:00 AM to 8:00 PM

ESALs and Future Traffic Volumes for Highway 076

From RefPoint 115 To RefPoint 150

ESAL Calculations are based on the following:
Build Year: 2006
Design Life: 30 years
Number of Lanes: 4

Rigid ESALs

Route	Ref Point	End Ref Point	Length (Miles)	AADT	AADT YR	YR20 Factor	AADT Single Trucks	AADT Comb. Trucks	AADT 2036	AADT Single Trucks 2036	AADT Comb. Trucks 2036	18 KiP ESALs
076A	115.197	124.756	9.567	8,400	2004	1.42	320	2240	14,045	535	3,745	26,069,784
076A	124.756	148.880	24.191	6,400	2004	1.24	120	1620	8,858	166	2,242	16,547,633

If you notice an error, bug or have any questions, Please E-mail us.

ESALs and Future Traffic Volumes for Highway 076

From RefPoint 115 To RefPoint 150

ESAL Calculations are based on the following: Rigid ESALs
Build Year: 2006
Design Life: 22 years
Number of Lanes: 4

Route	Ref Point	End Ref Point	Length (Miles)	AADT	AADT YR	YR20 Factor	AADT Single Trucks	AADT Comb. Trucks	AADT 2028	AADT Single Trucks 2028	AADT Comb. Trucks 2028	18 KiP ESALs
076A	115.197	124.756	9.567	8,400	2004	1.42	320	2240	12,634	481	3,369	17,934,423
076A	124.756	148.880	24.191	6,400	2004	1.24	120	1620	8,243	155	2,087	11,651,147

If you notice an error, bug or have any questions, Please E-mail us.

APPENDIX C

Appendix C

Life Cycle Cost
Rubblization with Hot Mix Asphalt Pavement

Life Cycle Cost Calculations

Darwin Pavement Design Sheet

User Cost Calculations
- Construction - Cross-over Traffic Control
- Rehabilitation Cycles - Single Lane Closure 6 AM to 8 PM

CDOT Traffic
- 20-Year ESALs for Thickness Design
- 10-Year Volumes – Rehabilitation
- 20-Year Volumes – Rehabilitation
- 30-Year Volumes – Rehabilitation

1993 AASHTO Pavement Design

DARWin Pavement Design and Analysis System

A Proprietary AASHTOWare Computer Software Product

Life Cycle Cost Module

HMA over Rubblized PCCP

Life Cycle Cost Data

Summary

Analysis Period	40 years
Project Length	3 mi
Discount Rate	4 %
Number of Lanes in One Direction	2
Type of Roadway	Divided

Total Costs -- Using NPV on a basis of total costs for both directions

Initial Construction Cost	$4,057,417
Rehabilitation Cost	$2,016,017
Salvage Value	$0
Total Cost	$6,073,435

Initial Construction

AC Pavement Initially Constructed

Construction Year	2005
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for both directions

Information Type	Source	Costs at Year of Construction (One Direction)	Net Costs
Construction	DARWin Calculated	$1,956,571.07	$3,913,142.15
Maintenance	DARWin Calculated	$72,137.59	$144,275.17
Total	-	$2,028,708.66	$4,057,417.32

Rehabilitation #1

2" Overlay

Rehabilitation Year	2015
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for both directions

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$503,718.75	$680,588.67
Maintenance	DARWin Calculated	$81,839.59	$110,575.79
Total	-	$585,558.34	$791,164.46

Rehabilitation #2

2" Mill & 2" Overlay

Rehabilitation Year	2025
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for both directions

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$722,230.31	$659,232.97
Maintenance	DARWin Calculated	$72,137.59	$65,845.31
Total	-	$794,367.90	$725,078.28

Rehabilitation #3

2" Mill & 2" Overlay

Rehabilitation Year	2035
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for both directions

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$728,644.31	$449,309.28
Maintenance	DARWin Calculated	$81,839.59	$50,465.35
Total	-	$810,483.90	$499,774.63

Salvage Values

Salvage Year	2045

Cost Information -- Using NPV on a basis of total costs for both directions

Phase	Description	Source	Salvage Value	Net Value
Initial Construction	-	DARWin Calculated	$0.00	$0.00
Rehabilitation #1	-	DARWin Calculated	$0.00	$0.00
Rehabilitation #2	-	DARWin Calculated	$0.00	$0.00
Rehabilitation #3	-	DARWin Calculated	$0.00	$0.00

Initial Construction Maintenance Costs

Year Maintenance Costs Begin	2006

Annual Maintenance Costs	$1,617.00 per lane mi
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $72,137.59

Rehabilitation #1 Maintenance Costs

Year Maintenance Costs Begin	2015
Annual Maintenance Costs	$1,617.00 per lane mi
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $81,839.59

Rehabilitation #2 Maintenance Costs

Year Maintenance Costs Begin	2026
Annual Maintenance Costs	$1,617.00 per lane mi
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $72,137.59

Rehabilitation #3 Maintenance Costs

Year Maintenance Costs Begin	2035
Annual Maintenance Costs	$1,617.00 per lane mi
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $81,839.59

Initial Construction Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
HBP (Grading SX)(100)(PG 64-28)	T.L.	1	ton	$46.50	22,075	$1,026,506.84
10% Design Engineering	N.A.	NA	10%	$1,280,704.00	0	$128,070.40
18.1% Construction Engineering	N.A.	NA	lump sum	$231,807.42	1	$231,807.42
15% Traffic Control	N.A.	NA	15%	$1,280,704.00	0	$192,105.60
Net User Cost	N.A.	NA	lump sum	$123,884.01	1	$123,884.01
Rubblization of PCCP	T.L.	2	sq yd	$2.07	42,240	$87,436.80
Edge Drains	T.L.	2	linear ft	$8.35	15,840	$132,264.00
Pulverization of Shoulder	T.L.	3	sq yd	$1.40	24,640	$34,496.00

Non Discounted Costs (One Direction)

Traffic Lane	$1,280,703.64
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$675,867.43

Total Non Discounted Cost (One Direction) $1,956,571.07

Rehabilitation #1 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
10% Design Engineering	N.A.	NA	10%	$344,387.00	0	$34,438.70
18.1% Construction Engineering	N.A.	NA	lump sum	$62,334.05	1	$62,334.05
15% Traffic Control	N.A.	NA	15%	$344,387.00	0	$51,658.05
Net User Cost	N.A.	NA	lump sum	$10,901.00	1	$10,901.00
HBP 2"/50mm Overlay	T.L.	1	ton	$46.50	7,358	$342,168.95
Edge Drain Maintenance	T.L.	1	lump sum	$2,218.00	1	$2,218.00

Non Discounted Costs (One Direction)

Traffic Lane	$344,386.95
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$159,331.80
Total Non Discounted Cost (One Direction)	$503,718.75

Rehabilitation #2 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
10% Design Engineering	N.A.	NA	10%	$478,147.00	0	$47,814.70
18.1% Construction Engineering	N.A.	NA	lump sum	$86,544.61	1	$86,544.61
15% Traffic Control	N.A.	NA	15%	$478,147.00	0	$71,722.05
Net User Cost	N.A.	NA	lump sum	$38,002.00	1	$38,002.00
Removal Asphalt Mat (Planing)	T.L.	Milling	sq yd	$2.00	66,880	$133,760.00
HBP 2"/50mm Overlay	T.L.	1	ton	$46.50	7,358	$342,168.95
Edge Drain Maintenance	T.L.	2	lump sum	$2,218.00	1	$2,218.00

Non Discounted Costs (One Direction)

Traffic Lane	$478,146.95
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$244,083.36
Total Non Discounted Cost (One Direction)	$722,230.31

Rehabilitation #3 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
10% Design Engineering	N.A.	NA	10%	$478,147.00	0	$47,814.70
18.1% Construction Engineering	N.A.	NA	lump sum	$86,544.61	1	$86,544.61
15% Traffic Control	N.A.	NA	15%	$478,147.00	0	$71,722.05
Net User Cost	N.A.	NA	lump sum	$44,416.00	1	$44,416.00
Removal Asphalt Mat (Planing)	T.L.	Milling	sq yd	$2.00	66,880	$133,760.00
HBP 2"/50mm Overlay	T.L.	1	ton	$46.50	7,358	$342,168.95
Edge Drain Maintenance	T.L.	1	lump sum	$2,218.00	1	$2,218.00

Non Discounted Costs (One Direction)

Traffic Lane	$478,146.95
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$250,497.36
Total Non Discounted Cost (One Direction)	$728,644.31

Initial Construction -- Traffic Lane Dimensions

Layer	Material Description	Width (ft)	Thickness (in)
1	HMA Grading S PG 64-28	38	6
2	Rubblization of PCCP	24	8
3	Pulverization of Shoulder	14	6

Initial Construction -- Inner Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Initial Construction -- Outer Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Rehabilitation #1 -- Traffic Lane Dimensions

Layer	Material Description	Width (ft)	Thickness (in)
1	HBP 2"/50mm Overlay	38	2

Milling Thickness 2 in

Rehabilitation #1 -- Inner Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Milling Thickness - in

Rehabilitation #1 -- Outer Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Milling Thickness 2 in

Rehabilitation #2 -- Traffic Lane Dimensions

Layer	Material Description	Width (ft)	Thickness (in)
1	HBP 2"/50mm Overlay	38	2
2	Milling	38	2

Milling Thickness 2 in

Rehabilitation #2 -- Inner Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Milling Thickness 2 in

Rehabilitation #2 -- Outer Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Milling Thickness 2 in

Rehabilitation #3 -- Traffic Lane Dimensions

Layer	Material Description	Width (ft)	Thickness (in)
1	HBP 2"/50mm Overlay	38	2
2	Milling	38	2

Milling Thickness 2 in

Rehabilitation #3 -- Inner Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Milling Thickness 2 in

Rehabilitation #3 -- Outer Shoulder Dimensions

Layer	Material Description	Width (ft)	Inner Thickness (in)	Outer Thickness (in)

Milling Thickness 2 in

1993 AASHTO Pavement Design

DARWin Pavement Design and Analysis System

A Proprietary AASHTOWare Computer Software Product

Flexible Structural Design Module

Full Depth Asphalt Pavement (20 years)

Flexible Structural Design

18-kip ESALs Over Initial Performance Period	10,413,989
Initial Serviceability	4.5
Terminal Serviceability	2.5
Reliability Level	95 %
Overall Standard Deviation	0.44
Roadbed Soil Resilient Modulus	16,525 psi
Stage Construction	1
Calculated Design Structural Number	3.84 in

Specified Layer Design

Layer	Material Description	Struct Coef. (Ai)	Drain Coef. (Mi)	Thickness (Di)(in)	Width (ft)	Calculated SN (in)
1	Rubblized PCCP	0.25	1	8	24	2.00
2	HMA	0.44	1	6	24	2.64
Total	-	-	-	14.00	-	4.64

CDOT REPORT - Summary Input and Output for the Crossover Strategy

	INPUT DATA		
Project Name	Brush		
Freeway Name	I 76		
Input File			
Project Start Date			
Project End Date			
Design Speed	75 mph		
Speed Limit	75 mph		
Workzone Speed Limit	55 mph		
Grade	2.0 %		
Work Zone Length	3.00 miles		
Functional Class	Rural Interstate (Weekday)		
INBOUND		**OUTBOUND**	
Total Number of Lanes	2	**Total Number of Lanes**	2
Number of Open Lanes	1	**Number of Open Lanes**	1
Number of Temporary Lanes	0	**Number of Temporary Lanes**	0
AADT	4200	**AADT**	4200
Percentage of Single Unit Trucks	4.0 %	**Single Unit Trucks(%)**	4.0 %
Percentage of Combination Trucks	27.0 %	**CombinationTrucks(%)**	27.0 %
	OUTPUT SUMMARY		
	ADDITIONAL USER COST DUE TO WORKZONE		
TYPE OF WORK	**INBOUND COST**	**OUTBOUND COST**	**DURATION**
412-Rubbilization of PCCP	$49,461.79	$49,461.79	21
403-HBP (Asphalt) <= 3.0 inch	$74,422.22	$74,422.22	33
TOTAL ADDL. USER COST	$123,884.01	$123,884.01	54
TOTAL USER COST FOR NORMAL CONDITION (WITH NO WORKZONE)			
FOR A DURATION OF 54 DAYS : INBOUND = $609,737.09 OUTBOUND = $609,737.09			
Disclaimer:			
The values presented in this program are intended to provide guidelines only.			
Engineering judgement must be applied to use these values.			
No one but the user can assure that these results are properly applied.			

2006 Volume
Cross Over Lane Closure
24 Hour Closure

CDOT REPORT - Summary Input and Output for the Single Lane Closure Strategy

	INPUT DATA	
Project Name	Brush	
Freeway Name	I 76	
Input Filename		
Project Start Date		
Project End Date		
Design Speed	75 mph	
Speed Limit	75 mph	
Workzone Speed Limit	55 mph	
Grade	2.0 %	
Work Zone Length	3.00 miles	
Total Number of Lanes	2	
Number of Open Lanes	1	
Number of Temporary Lanes	0	
AADT, Directional	5258	
Percentage of Single Unit Trucks	4.0 %	
Percentage of Combination Trucks	27.0 %	
Functional Class	Rural Interstate (Weekday)	
	OUTPUT SUMMARY	
TYPE OF WORK	**ADDITIONAL USER COST DUE TO WORKZONE**	**DURATION**
403-HBP (Asphalt) <= 1.0 inch	$21,801.20	10
TOTAL ADDL. USER COST	$21,801.20	10
TOTAL USER COST FOR NORMAL CONDITION (WITH NO WORKZONE)		
FOR A DURATION OF 10 DAYS = $105,073.20		
Disclaimer:		
The values presented in this program are intended to provide guidelines only.		
Engineering judgement must be applied to use these values.		
No one but the user can assure that these results are properly applied.		

10-Year - 2016 Volume
Single Lane Closure
6:00 AM to 8:00 PM

CDOT REPORT - Summary Input and Output for the Single Lane Closure Strategy

	INPUT DATA	
Project Name	Brush	
Freeway Name	I 76	
Input Filename		
Project Start Date		
Project End Date		
Design Speed	75 mph	
Speed Limit	75 mph	
Workzone Speed Limit	55 mph	
Grade	2.0 %	
Work Zone Length	3.00 miles	
Total Number of Lanes	2	
Number of Open Lanes	1	
Number of Temporary Lanes	0	
AADT, Directional	6141	
Percentage of Single Unit Trucks	4.0 %	
Percentage of Combination Trucks	27.0 %	
Functional Class	Rural Interstate (Weekday)	
	OUTPUT SUMMARY	
TYPE OF WORK	ADDITIONAL USER COST DUE TO WORKZONE	DURATION
403-HBP (Asphalt) <= 1.0 inch	$25,944.32	10
202-Removal of Asphalt (Planing)	$12,057.86	5
TOTAL ADDL. USER COST	$38,002.18	15
TOTAL USER COST FOR NORMAL CONDITION (WITH NO WORKZONE)		
FOR A DURATION OF 15 DAYS = $184,020.39		
Disclaimer:		
The values presented in this program are intended to provide guidelines only.		
Engineering judgement must be applied to use these values.		
No one but the user can assure that these results are properly applied.		

20-Year - 2026 Volume
Single Lane Closure
6:00 AM to 8:00 PM

CDOT REPORT - Summary Input and Output for the Single Lane Closure Strategy

	INPUT DATA	
Project Name	Brush	
Freeway Name	I 76	
Input Filename		
Project Start Date		
Project End Date		
Design Speed	75 mph	
Speed Limit	75 mph	
Workzone Speed Limit	55 mph	
Grade	2.0 %	
Work Zone Length	3.00 miles	
Total Number of Lanes	2	
Number of Open Lanes	1	
Number of Temporary Lanes	0	
AADT, Directional	7023	
Percentage of Single Unit Trucks	4.0 %	
Percentage of Combination Trucks	27.0 %	
Functional Class	Rural Interstate (Weekday)	
	OUTPUT SUMMARY	
TYPE OF WORK	**ADDITIONAL USER COST DUE TO WORKZONE**	**DURATION**
403-HBP (Asphalt) <= 1.0 inch	$30,346.94	10
202-Removal of Asphalt (Planing)	$14,069.26	5
TOTAL ADDL. USER COST	$44,416.21	15
TOTAL USER COST FOR NORMAL CONDITION (WITH NO WORKZONE)		
FOR A DURATION OF 15 DAYS = $210,385.18		
Disclaimer:		
The values presented in this program are intended to provide guidelines only.		
Engineering judgement must be applied to use these values.		
No one but the user can assure that these results are properly applied.		

30-Year - 2036 Volume
Single Lane Closure
6:00 AM to 8:00 PM

ESALs and Future Traffic Volumes for Highway 076

From RefPoint 115 To RefPoint 150

ESAL Calculations are based on the following:
Build Year: 2006
Design Life: 10 years
Number of Lanes: 4

Flexible Pavement ESALs

Route	Ref Point	End Ref Point	Length (Miles)	AADT	AADT YR	YR20 Factor	AADT Single Trucks	AADT Comb. Trucks	AADT 2016	AADT Single Trucks 2016	AADT Comb. Trucks 2016	18 KiP ESALs
076A	115.197	124.756	9.567	8,400	2004	1.42	320	2240	10,517	401	2,804	4,770,306
076A	124.756	148.880	24.191	6,400	2004	1.24	120	1620	7,322	137	1,853	3,213,392

If you notice an error, bug or have any questions, Please E-mail us.

ESALs and Future Traffic Volumes for Highway 076

From RefPoint 115 To RefPoint 150

ESAL Calculations are based on the following:
Build Year: 2006
Design Life: 20 years
Number of Lanes: 4

Flexible Pavement ESALs

Route	Ref Point	End Ref Point	Length (Miles)	AADT	AADT YR	YR20 Factor	AADT Single Trucks	AADT Comb. Trucks	AADT 2026	AADT Single Trucks 2026	AADT Comb. Trucks 2026	18 KiP ESALs
076A	115.197	124.756	9.567	8,400	2004	1.42	320	2240	12,281	468	3,275	10,413,989
076A	124.756	148.880	24.191	6,400	2004	1.24	120	1620	8,090	152	2,048	6,782,511

If you notice an error, bug or have any questions, Please E-mail us.

ESALs and Future Traffic Volumes for Highway 076

From RefPoint 115 To RefPoint 150

ESAL Calculations are based on the following:
Build Year: 2006
Design Life: 30 years
Number of Lanes: 4

Flexible Pavement ESALs

Route	Ref Point	End Ref Point	Length (Miles)	AADT	AADT YR	YR20 Factor	AADT Single Trucks	AADT Comb. Trucks	AADT 2036	AADT Single Trucks 2036	AADT Comb. Trucks 2036	18 KiP ESALs
076A	115.197	124.756	9.567	8,400	2004	1.42	320	2240	14,045	535	3,745	16,931,050
076A	124.756	148.880	24.191	6,400	2004	1.24	120	1620	8,858	166	2,242	10,707,355

If you notice an error, bug or have any questions, Please E-mail us.