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Final Report, Phase I

OPTIMIZATION OF CONCRETE PAVEMENT MIX DESIGN IN COLORADO

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August 2002

COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

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OPTIMIZATION OF CONCRETE PAVEMENT MIX DESIGN IN COLORADO

PHASE I

Written by:

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*An Executive Summary Report
Developed by The Transtec Group, Inc.
26 June 2002*



Executive Summary

In this report, an engineering analysis is documented representing Phase I of a study to evaluate potential durability issues stemming from the use of lowered cement contents in portland cement concrete pavement (PCCP) mixes specified by the State of Colorado Department of Transportation (CDOT).

CDOT, like many state DOT's, is recognizing that the mere addition of more cement to already cement-rich mixes may not be the best approach in addressing long-term PCCP durability. As a result, materials optimization has once again become a hot topic. The continued escalation of costs of concrete-making materials (especially cement), coupled with pressure to maintain or even extend the durability of PCCP, has led to the identification of this important research topic.

This phase of the overall study has revealed that concrete pavements constructed with a lower-than-normal cement content (20% replacement with Class F fly ash) possessed durability characteristics expected of any typical concrete paving mixture. Although some of the concrete pavements evaluated in this study did possess moderate to high distress levels, the structural design is believed to be the predominant factor leading to the observed failures.

This project has resulted in the beginning of a knowledge base of concrete pavement durability. Coupled with further evaluation of in-service pavements, along with a controlled laboratory testing factorial, additional data can be added to that knowledge base. Subsequent integration of the knowledge base with modeling can ultimately lead to a concrete mixture optimization system that would allow for rapid identification and proportioning of concrete-making materials.

Background

In July 2001, the Colorado Department of Transportation (CDOT) initiated study number 22.50 titled "Optimization of Mix Design for Concrete Pavements in Colorado." In December 2001, CDOT procured the services of The Transtec Group, Inc. (Transtec) to assist in this endeavor. The background leading to the initiation of the study stemmed from the success of a high-performance concrete (HPC) study conducted by CDOT during the previous year (1). That study concluded that reducing the cement content of structural concrete by substituting it with 20% Class F fly ash could result in a durable mix that is anticipated to meet the durability requirements for the structure. An assessment was subsequently made of the potential costs and benefits of using a fly ash replacement (as compared to an addition) in paving concrete. Appendix A includes the result of this CDOT analysis. Furthermore, it was recognized that although similar fly ash replacements had been used in paving mixes on previous projects, no coordinated effort had been conducted to evaluate the durability of these pavements to date.

Objective

The objective of this analysis is to demonstrate, using sound engineering fundamentals, the potential impact (if any) to the durability of concrete pavements constructed with mixes of lower-than-normal cement contents. Within the State of Colorado, there are a number of existing concrete pavements with significant fly ash replacements. Within the scope of this project, the project team will evaluate the condition of five of these pavements and learn from the observations of the existing condition. Taking into account the traffic and environment that the pavements have been exposed to, an assessment will be made of the durability of the mixes used in these pavements compared to mixes not containing fly ash.

Analysis Approach

The work executed under this effort was carried out in six tasks, summarized as follows:

1. Conduct a brief literature review with respect to aspects of design, materials selection, and construction related to concrete pavements containing lower cement contents. Definitions of durability and factors to assess durability in the early life of the PCCP were also derived during this task.
2. Make a preliminary presentation to the project panel, presenting the results of the work conducted to date, and identifying the proposed data collection and analysis plan.
3. Conduct a field investigation of the durability and performance of five existing PCCP projects in the State of Colorado. These evaluations included:
 - Visual condition surveys.
 - Investigation of design and construction records contained by the various DOT offices. This information included mix design, materials suppliers, construction dates, and other key design, materials, construction, and climatic data.
 - Collection of pavement management records for the sections.
4. Reduce, interpret, and document the results of the field-testing, identifying durability and performance issues that were observed. Relationships can then be drawn between the observations and the supplementary information that was collected such as the mix designs.
5. Based on the results from this phase, prepare a workplan for Phase II that includes the collection of additional information necessary to address the overall study objectives.
6. Make a presentation to the project panel, presenting the results of the work conducted in Phase I, and the recommendations for additional work, if any is deemed necessary.

Defining Concrete Pavement Durability

To successfully execute the work in this effort, one of the first steps required is to establish a definition for durability of paving concrete. During the literature search, a number of definitions were identified including:

In Properties of Concrete (2), where Neville states:

Durable concrete should maintain its required strength and serviceability during its service life. It should withstand the processes of deterioration to which it can be expected to be exposed.

Dolch (3) stated that:

Durability can be categorized into:

- Resistance to Cracking,
- Resistance to Alkali-Aggregate Reaction, and
- Resistance to Freeze/Thaw Damage.

From the ACI Committee on Cement and Concrete Terminology (4):

Durability is the ability of concrete to resist:

- Weathering action,
- Chemical attack,
- Abrasion, and
- Other conditions of service.

Finally, as a result of the CDOT study on HPC bridges, Ardani stated (5):

Durability can be improved by:

- Reducing shrinkage cracking,
- Reducing thermal cracking,
- Reducing permeability,

While maintaining workability and strength.

For purposes of this study, the project team proposed the following definition of Durability:

A durable concrete pavement should meet or exceed the intended design life. It should therefore possess:

- A low potential for cracking,
- Low permeability (to resist environmental damage), and
- A sound and smooth riding surface.

Literature Search Results

A literature search was conducted in this project to identify various issues related to the use of lower-than-normal cement contents in paving concrete. As mentioned previously, one of the driving forces behind the execution of this effort was the successful placement of high-performance concrete with lower-than-normal cement contents on bridge decks (1). It was concluded in that study that the use of lower cement contents (replacing 20% of the cement with Class F fly ash) reduced the heat of hydration, and thus the probability of thermal shrinkage cracking.

Other studies have identified similar findings. One of the premier publications recently published on this topic is ACI Monograph #11 titled “The Visible and Invisible Cracking of Concrete,” by Richard Burrows (6). In fact, the caption on the cover page of this reference states, “changing cement specifications could increase concrete durability.” Mr. Burrows raises the question, “are lean concretes durable?” The response includes numerous references to previous studies. One of the citations is a Portland Cement Association (PCA) study where mixes with as little as four-sacks (376 lbs/cu.yd.) of cement and water-to-cement ratios of 0.66 to 0.79 performed excellently after 25 years of exposure to adverse climates (7).

More recently, Dr. John Myers of the University of Missouri at Rolla investigated the permeability of various high-performance concretes (8). It should be noted that the second “bullet” in the proposed definition for durable concrete was for it to be of low permeability. Dr. Myers investigated 175 different concrete mixes in his study – containing different proportions of cement and fly ash. He concluded that mixtures with fly ash had significantly (approximately 60%) lower permeability than concretes proportioned with straight cement.

Finally, Drs. P.S. Mangat of Sheffield Hallam University and J.M. Khatib of the University of Glamorgan studied the influence of fly ash and other cement substitutes on the resistance of concrete to sulfate attack (9). They concluded that 22% or more replacement of the cement with fly ash could significantly resist sulfate attack, even when exposed to an aggressive saturated environment.

Field Evaluation

This section describes the various aspects of the field investigation conducted during this project. The following sections identify the sites, discuss the work plan that was executed during the evaluation task, and discuss the key observations and findings.

Field Site Identification

The intent of this effort is to evaluate in-service concrete pavements that were constructed with lower-than-normal cement contents. Five sites were selected by the project panel that met this criterion. These sites include:

1. Interstate 70 near Deer Trail (Mile Marker 322.6 to 329.0)
2. Interstate 76 near Barr Lake (Mile Marker 23.5 to 31.2)
3. Interstate 76 near Roggen (Mile Marker 50.1 to 61.9)
4. U.S. Highway 34 east of Greeley (Mile Marker 115.2 to 120.0)
5. Interstate 25 near Johnson Corner (Mile Marker 240.2 to 254.2)

Field Evaluation Details

On February 4, 2002, Transtec initiated the field evaluation visit. The first four sites identified above were visited on this day beginning around 9am, and concluding around 4pm. The fifth site (I-25) was surveyed the following morning. The weather was sunny but cool during the survey.

Dr. Robert Otto Rasmussen and Mr. J. Mauricio Ruiz conducted the field evaluation. It included video and photographic documentation of the field sites as well as written notes. Due to the lack of traffic control, no quantitative data was collected during the field visit.

Preliminary Data Collection

Prior to the field evaluation, CDOT provided Transtec with historical information about the field sites. This information included:

1. Plan or as-built sheets including the stationing, quantities, and typical sections;
2. Pavement management system (PMS) data;
3. Traffic loading information;
4. Approved mix designs and laboratory test results of the concrete; and
5. Pavement design information (on some sections).

Key Observations and Findings

The following sections describe the observations that were made during the field evaluation. Typical photographs of the distresses that were observed can be found in Appendix B. Summary observations and interpretation from these sites is provided in the next section.

Site 1: I-70 near Deer Trail (MP 322.6 to 329.0)

General Observations:

- Light traffic with large percentage of trucks.
- Pavement transversely tined with skewed joints.
- Overall evaluation demonstrated that the pavement is in good condition.
- Good ride quality.
- Evidence of grinding noted on various segments, especially in the WB direction.

Eastbound Direction:

Section 2080+00

- Some longitudinal cracking observed.
- Cracks have been routed and sealed.
- Cracking could be due to loss of support or from late sawing.

Section 2085+00

- Additional cracks observed.
- One or two joints observed to have some faulting (just before the bridge structure).
- Cracks show some exposed aggregate, and spalling is evident.
- Section is on a fill section, with a culvert structure appearing to be backed up with debris.
- Underlying hot-mix asphalt layer observed to extend a few feet beyond the edge of the concrete.
- Significant spalling observed at a longitudinal crack parallel and adjacent to the shoulder.
- Tie-bar “scars” observed. Possibly due to lack of compaction (vibration) from the tie-bar insertion both between the lanes, and at the shoulder.
- At the “scars”, no visible spalling, scaling, or durability type issues.
- After transition from cut to fill section, significant longitudinal cracking was observed.
- Cracking appears to be crescent shaped, possibly due to loss of support or sawing that was of inadequate depth or timeliness.
- Cracks primarily observed in the loaded (right) lane.
- Evidence of spalling at the cracks.
- Some patching of the spalls noted with an asphalt mix, however additional spalling has progressed after patching.
- Natural grade going from north to south (there is a creek running parallel to the freeway on the south side).
- Fills seem to be higher on the eastbound direction.

Westbound Direction:

Section 2085+00

- In this direction (as opposed to the eastbound observations at the same station), no cracking is noted.
- No visible structural distress.

Site 2: I-76 near Barr Lake (MP 23.5 to 31.2) – Eastbound Only

Eastbound Direction:

MM 24.4

- Discoloration on shoulder - possibly plastic shrinkage cracking or alkali attack.
- Joints sealed with asphalt.
- Number of mid-panel cracks transverse and longitudinal directions.
- Significant traffic with a high percentage of trucks.
- “Random” joint spacing at 18, 13, 12, and 19 ft.
- Some popouts observed on the surface.
- Mid-panel cracking primarily observed on longer joint spacings (18 and 19 ft.).
- Shoulder looks of different color although timing coincides.

Station 437+00

- Some corner cracks observed with severe spalling.
- Slight polishing observed on wheelpath.
- Longitudinal cracking observed in wheelpath (possibly fatigue related).
- Some severe spalling in discrete areas, primarily in the right lane.
- Some longitudinal cracking on passing lane with significant spalling.

MM 27

- Longitudinal cracks in the center of the right lane.
- Passing lane also showing some longitudinal cracking.

MM 30.4 (Station 765+00)

- High severity longitudinal cracking.
- Heavily spalled, commonly treated with HMA patching.
- Significant polishing evident, tining virtually gone.
- Coarse aggregate appears to be siliceous.
- Longitudinal crack occurring just off the longitudinal joint possibly early-age-related (late sawing).
- Transverse cracking at mid-panels observed, with deep spalls noted at many of the cracks.
- Visible transverse cracking on polished area (also noted on westbound lane with no tinning) possibly plastic shrinkage cracking.
- Some of the transverse cracks go through some of the aggregates

Station 762+00

- Some white powder observed coming out of the cracks – possibly due to alkali-silica reaction.

Site 3: I-76 near Roggen (MP 50.1 to 61.9)

General Observations:

- Smooth ride.
- Some roughness at the joints, possibly due to faulting or curled/warped slabs.
- Some longitudinal trails noticed – possible cause: snow plow or vehicle damage.
- Slight fills and cuts in the terrain.

Eastbound Direction:

MM 52

- Concrete appears to be very sound.

Station 1883+00

- Some minor popouts observed.
- Some minor spalling at the joints, possibly during sawcutting.
- Skewed joints – 12 to 15 joint spacing – random pattern.
- One corner break, low severity.

Station 1884+00

- Periodic asphalt-sealed joints noted, possibly construction joints.

MM 59

- One or two longitudinal cracks.

Westbound Direction:

MM 62

- Some longitudinal cracking in the passing lane.

MM 60 to 61

- Longitudinal cracking noted in PMS data is due to grooves in the pavement, not cracks.
- No polishing in wheelpath apparent.
- Ride quality is good.

MM 58.5

- A few longitudinal cracks in the passing lane.

MM 57

- Slight wearing in the wheelpaths.

Site 4: US 34 east of Greeley (MP 115.2 to 120.0) – Eastbound Only

Eastbound Direction:

Station 106+00

- Ride quality is a little rough – some minor cracking observed.

Station 134+00 to 135+00

- Transverse cracks noted at mid-panel – hypothesized to be early-age.
- Scaring of the surface noted at many of the tie bar locations.
- Some eroding of the paste around tining is noted.
- Uniform tining observed to produce resonant noise.
- Some polishing of aggregate at wheelpath is noted.
- Many of the transverse cracks noted to occur at the 1/3 in from the sawed joint.

MP 116

- Much smoother ride.

MP 116.7

- Transverse crack noted – hypothesized as early-age.
- Section not significantly distressed.

Site 5: I-25 near Johnson Corner (MP 240.2 to 254.2)

Southbound Direction:

- Rough ride.
- Heavy traffic, high percentage of trucks.

MM 253.6

- Surface of pavement heavily polished on both right and left lanes.
- Corner cracks – possibly due to relatively thin slabs (noted from plans).
- Some popouts noted.
- A number of corner cracks noted on the approach end of the slab in the driving lane.
- Numerous faulted cracks, concrete has punched into subbase material.

- Although there is significant cracking, only minor spalling is observed.
- A number of concrete patches are present and appear to be aged due to their surface polishing.
- Shoulder doesn't appear to have been placed at same time as main lanes.

Exit 252

- Significant distress on driving lane with some dropoff between lane and shoulder.
- Some spalled cracks have been sealed with asphalt.
- Faulting of the pavement (especially between patch and pavement) up to 3/8" to 1/2" at some joints.
- Numerous corner cracks, longitudinal cracks, and PCC patches observed.
- Longitudinal cracks at mid-slab and transverse cracks adjacent to the shoulder.

After Exit 252

- Significant severe cracking both longitudinal at mid-slab, and transverse from mid-slab to the shoulder.
- Most of the cracking is on the right lane.
- Significant faulting.
- Many of the cracks are wide.
- Variable condition – with some sections in good condition, and others with severe cracking.

After Exit 251

- A shift is observed in the location of the distress, now concentrated more on the centerline (in the right lane though).
- After a few hundred feet, the concentration of distresses is back on the right side of the right lane.

MM 249 to 248 (Station 458+00)

- Vertical tangent with a moderately steep grade.
- Some cracking observed, sealed, with no evidence of spalling.
- No significant structural distresses.
- Random joint spacing 14.5', 12', 13', 15'.

MM 248 to 246

- Significant faulting causing poor ride quality.
- Distresses concentrated on center portion of right lane.

MM 245

- Large number of patches.
- Significant spalling.

Northbound Direction:

- Distresses observed in the passing lane, not observed to this severity on the southbound direction.
- Similar roughness characteristics.
- Numerous shattered slabs and faulting observed.

MM 245

- Better condition on this direction (as opposed to southbound).
- Not as much distress.
- Observed distresses concentrated on passing lane – mainly corner cracking that appears to be low severity.
- Spalling and corner cracking on centerline joint.

MM 247

- Distresses concentrated around centerline, all seem to be low severity and asphalt sealed.

MM 248

- Distresses concentrated around centerline.
- Cracking more pronounced on the passing lane.

MM 250

- Some patching observed.

MM 251

- Some faulting and shattered slabs noted near the centerline and the passing lane.

MM 253

- Smoother ride and not much distress toward the north end of the project.
- Some minor flapping of the joints noted.
- Distressed slabs on leave end of bridge structure, with significant faulting.

Discussion

By definition, optimization is “the procedures used to make a system (or design) as effective (or functional) as possible.” Two key terms in this definition include “system” and “effective.”

Most seasoned technologists will agree that concrete is a “system.” Given the constraints that we are under in today’s paving projects, concrete will simply not perform reliably if we haphazardly “throw together” the main ingredients: rock, sand, cement, and water. When concrete is expected to endure under adverse conditions, it must be engineered. Engineering includes an understanding and control of the system (process): from material selection to mixing to transportation to placement to curing. In controlling the process, each of the decisions made along the way include places where optimization can be performed.

The second key term, “effective,” can (in the case of concrete) take on many different meanings. For example, if you are responsible for placing or finishing the concrete, you may consider the workability of the mix to be the most important criterion. In fact, many times water is added in the field to improve this property. As an inspector given the charge to make sure the concrete “meets the spec”, the strength of the concrete may be of greatest concern. If you are the owner of the contracting firm, the bottom line is important, so an optimum mixture will be based largely on the lowest cost. Other factors that a concrete can be optimized for include segregation susceptibility, permeability, density, heat of hydration, toughness, volume stability, and a number of durability-related measures.

Properties versus Performance

Optimization of a concrete mixture first requires identification of what criteria are being optimized. These criteria can be loosely categorized into either concrete properties or performance indicators.

Traditionally, if optimization is performed at all, it is done to satisfy a number of properties. For example, a minimum strength, maximum permeability, or a maximum stiffness is often specified, and the concrete is optimized to meet these limits at the lowest cost with reasonable workability.

Figure 1 illustrates how optimization in this fashion may be done. By selecting the criteria and knowing what concrete-making constituents are available, optimization can be conducted by utilizing models and/or performing trial batches. The models commonly used include statistical models that identify trends in the value of a property (e.g., strength) as a function of the constituent proportions (e.g., cement content).

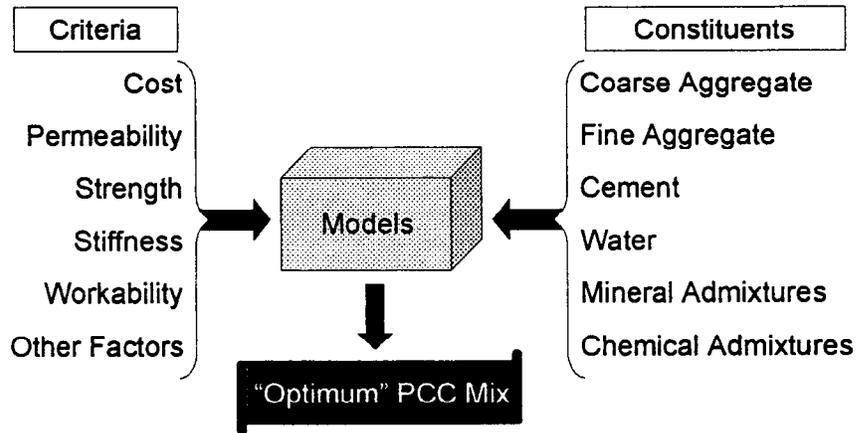


Figure 1. Property-driven Optimization of a Concrete Mixture

The next generation of concrete optimization, however, is illustrated in Figure 2. In this figure, in place of concrete properties, are performance and durability indicators. Although the resulting system is technically more complex, the result is much more beneficial to the user. Although the specifications we use today are primarily property-driven, having a performance-driven system accommodates the next generation of doing business. With performance-related, performance-based, and warranty type specifications and contracts on the horizon, performance prediction is the key. The need for a means to optimize the selection and proportions of the concrete-making constituents becomes clear.

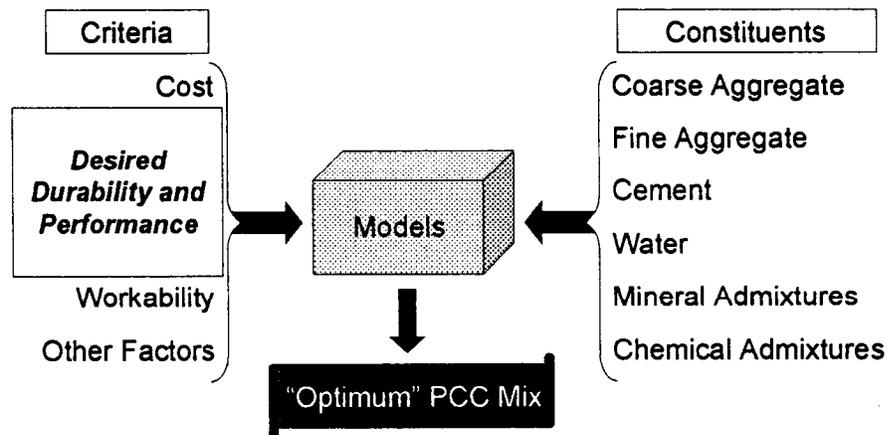


Figure 2. Property and Performance-driven Optimization of a Concrete Mixture

Summary Observations

In order to truly understand the link between concrete mixtures and durability in the State of Colorado, a knowledge base should be developed with the data necessary to verify and validate the “models” listed in Figures 1 and 2. This phase of the study serves to begin to build this dataset – more specifically, to explore the potential durability impacts of reducing the cement content normally used on today’s paving projects. The five field sites visited in this effort all were constructed with lower cement mixes. Table 1 summarizes the mix designs as reported to Transtec. Table 2 lists additional information about the sites.

Table 1. Summary of Concrete Mixture Proportions on the Field Sites

Highway	Cement (lb/yd ³)	F. Ash (lb/yd ³)	Water (lb/yd ³)	C. Agg (lb/yd ³)	F. Agg (lb/yd ³)	AEA (oz/ yd ³)	WR (oz/yd ³)	Fly Ash	w/c	w/b
								Replacement & Class		
I-70	455	110	265	1700	1360	5.0	–	19% (C)	0.58	0.47
I-76 (W)	452	113	250	1790	1295	8.0	–	20% (F)	0.55	0.44
I-76 (E)	452	113	210	1715	1393	6.5	30.0	20% (F)	0.46	0.37
US-34	452	113	245	1710	1400	4.3	24.4	20% (F)	0.54	0.43
I-25	455	110	250	1890	1160	8.0	25.0	19% (F)	0.55	0.44

Table 2. Other Pertinent Information about the Field Sites

Highway	Begin MM	End MM	Appx. Length (miles)	Appx. Opening Date	2000 ADT	% Trux	Appx. Age (years)	7-day Compr. Str. (psi)	28-day Compr. Str. (psi)	PCCP Thix (in.)	Support/ Pavement Type
I-70	322.6	329.0	6.4	May '91	8,168	43%	11	3435	4605	10.0	UBOL
I-76 (W)	23.5	31.2	7.7	Apr '82	10,470	23%	20	3190	4050	8.0	4" LCB
I-76 (E)	50.1	61.9	11.8	Jan '92	11,256	27%	10	4100	–	8.5	UBOL
US-34	115.2	120.0	4.9	Jan '92	7,398	14%	10	4466*	–	8	AB
I-25	240.2	254.2	14.0	Jun '85	50,066	13%	17	4090	4720	7.75	UBOL

* Estimated from 22, 44, and 68 hr. strengths

Of the field sites that were observed, the I-25 site was found to be in the poorest condition. Significant distress modes included mid-panel cracking in both the transverse and longitudinal directions. Spalling and punchouts were also observed throughout this project. As a result of these structural failures, significant roughness was also present. The western I-76 site also had a number of areas with significant structural failure. Although not as severe as the I-25 project, the distresses were significant enough to lead to a moderately poor ride quality.

The eastern I-76 project was found to be in good condition. Although minor amounts of structural distress were noted, the ride quality was found to be acceptable. I-70 and US-34 were observed to be in good to excellent condition. Both of these pavements are very smooth, especially the US-34 project. Some structural distress was noted, but hypothesized to be caused by early-age events such as late sawing or inadequate sawcut depth. A subsequent evaluation of I-70 by CDOT noted that the longitudinal joints were cut shallow where cracking was evident.

Other observations included “scarring” of the surface at the tie bar locations observed on both the I-70 and US-34 projects. Improper consolidation of the concrete immediately above the tie bars is suspected. Discoloration of the surface was noted, but no significant disintegration of the concrete was found. On the western I-76 location, some cracks were found to have a white-colored residue. This residue may simply be deicing salt crystals, or it may instead be indicative of a chemical reaction, possibly alkali-silica. However, crack patterns that are typically observed in conjunction with a severe chemical reaction were not noted. A petrographic evaluation of these pavements should reveal additional information.

Comparative Analysis of Observed versus Predicted Durability

In order to assess the durability of these pavements as compared to comparable pavements constructed of mixtures without fly ash replacement, a cursory analysis was performed of the predicted number of loads to failure compared to the actual traffic loading. The 1986/93 AASHTO Guide procedure was used to assess the predicted loads to failure: being defined as a terminal serviceability level of 2.5 (10). By making a number of assumptions in addition to knowledge of some of the input to the design procedure, the results of this analysis are summarized in Table 3.

Table 3. Summary of Remaining Life Analysis

Highway	Estimated Cumulative ESAL's	Calculated Cum. ESAL's to Failure	% of Pavement Life Consumed	% of Pavement Life Remaining
I-70	8,000,000	30,900,000	26%	74%
I-76 (W)	7,900,000	5,100,000	156%	0%
I-76 (E)	4,800,000	16,800,000	29%	71%
US-34	1,800,000	6,800,000	27%	73%
I-25	17,600,000	8,500,000	208%	0%

Comparing the analytical approach adopted herein, and comparing it to the field observations, it appears that the predictions made of the remaining life coincide with the field observations. Coupled with the lack of supporting evidence of durability-related failures, the project team finds that these concrete mixtures perform as expected of any typical concrete pavement under similar loading conditions.

Other State Specifications

As part of the information search of this effort, the project team queried concrete mixture specifications from a number of other states. The query included identification of provisions for cement replacement with fly ash and other cementitious and/or pozzolanic materials. Table 4 summarizes the results of this investigation. As can be seen in the table, numerous states allow the use of pozzolanic substitution in their concrete mixtures. Some states, for example Texas, encourage the use of pozzolans as a means to control high set temperatures, which has been identified as a source of adverse durability.

Proposed Phase II Plan

Given the complexity involved, is it even possible to optimize a mix? For example, if the optimum mix that is the lowest cost is radically different from the optimum mix to best resist chemical attack, then how does one choose which one to build? With the large number of variables in the process that can be controlled, coupled with the large number of potentially competing factors that define an optimum mix, both a knowledge base and computerization must be key components of the solution.

This project has served as the start of a knowledge base. This knowledge base can be expanded, possibly by assembling a controlled experiment of various elements in the overall process. However, computerization is another important step towards the goal of optimizing for cost-effective durable concrete. There currently exist numerous mathematical models to predict the various components of the optimization process. These models can be calibrated to Colorado conditions, allowing the user to quickly assess what an incremental change in any variable (e.g., cement content) might have on the overall cost, strength, permeability, and other factors. Furthermore, the calibrated models can be used to weigh these numerous factors for which the mix is optimized. In this way, an objective balance can be struck between competing factors.

These goals are high, and reaching them is probably beyond the capabilities of this project alone. However, if a continuation of this study is done with the knowledge of other past and ongoing efforts, the result can be a powerful system for optimizing concrete paving mixtures that is localized for Colorado conditions.

Therefore, the team proposes a second phase that includes some additional field evaluation at the five field sites previously visited: collecting samples for testing in the laboratory. In addition, a carefully designed experiment is proposed for evaluating combinations of concrete-making materials. By measuring properties that are desired to be optimized, along with other properties that may feed into performance predictions, the net result can be a solid framework for an optimization system. The following sections briefly expand on these two elements in more detail.

Table 4. Summary of Other State DOT Concrete Specifications.

State	Source/ Spec.	Spec. Year	Min. Cement Content (lb./yd ³)	Fly Ash Replacement Specifications
Texas	§421.2	1995	472	20% to 35% by volume Up to 40% total for Class IP Cement
Arizona	–	–	564	Max of 20% by weight Minimum replacement ratio of 1.2:1
California	§40 §90	1999	506	15% to 20% of all Pozzolans
North Dakota	§802	1997	517 (incl. FA)	20% Fly Ash replacing 15% Cement by weight
South Dakota	§605.3	1998	None	10% to 15% of Cement replaced by weight Replacement ratio of 1.25:1 by weight
Kansas	–	–	520	Class F Fly Ash Max of 25% Class C Fly Ash Max of 15%
Iowa	§2301 IM 529	2002	10.8% vol. of concrete	Max of 15% for primary paving (by weight) Max of 20% for other paving (by weight)
Minnesota	§3103 §3115	2000	–	Max of 20% for interground Max of 15% for blended
Illinois	§1010 §1020	2000	564	Class F Max of 15% by wt., ratio of 1.5:1 Class C Max of 20% by wt., ratio of 1.25:1

Completion of Field Evaluation

In this task, it is proposed that a number of representative samples of the concrete from the five field sites be collected for further evaluation in the laboratory. Laboratory testing should include:

- Strength tests of the concrete – splitting tensile (ASTM C496) is the preferred mode, but can be supplemented with compressive (ASTM C39) testing.
- Elastic modulus testing (ASTM C469)
- Coefficient of thermal expansion (AASHTO TP60 or similar)
- Petrographic evaluation (ASTM C856)

Mid-panel and joint/crack falling-weight deflectometer testing is also suggested to assess both the in-situ stiffness and load transfer. Interpretation of load transfer data could be further improved if diurnal joint movements are simultaneously measured using a Demec or similar device. Finally, collection of (or access to) inertial profile data from the site can assist in determining possible modes of distress.

Laboratory Factorial Evaluation

In this task, a controlled evaluation would be conducted of mixes consisting of representative cements, pozzolans, aggregates, and admixtures commonly used in concrete pavements in the state. The mix proportions would be determined after the set of concrete-making materials is decided upon, but may consist of several dozen combinations. For each batch, a number of tests could be conducted including:

- Strength tests at 3 and 28 days;
- Slump or a more fundamental workability characterization (e.g., the new FHWA device); and
- Rapid chloride permeability or a similar more fundamental measure (e.g., the SHRP device).

On a subset of these mixtures (due to the higher cost), the following tests could be performed:

- Heat of hydration (using adiabatic calorimetry);
- Coefficient of thermal expansion; and
- Drying shrinkage and relaxation creep potential.

The cost of each of the mixes will also be derived based on unit costs of each of the constituents. Once this information is collected, it can be used, along with other anecdotal and field evidence, to derive a basic optimization system. A schematic of this process is shown in Figure 3. The end result is a powerful tool that can be employed by the state of Colorado for use in specifying more cost-effective and better performing concrete mixtures.

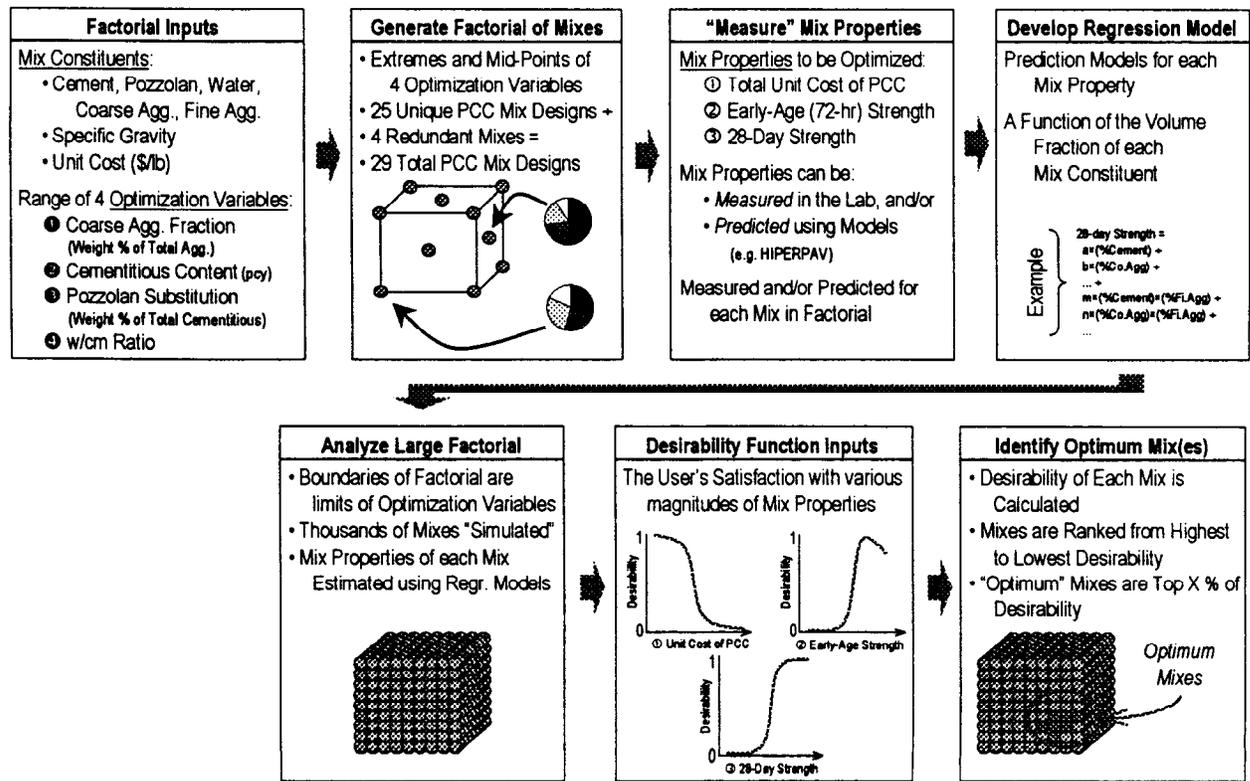


Figure 3. Schematic of Optimization Procedure for Concrete Mixes.

Summary and Conclusions

In this report, documentation is provided on the first phase of a study with the objective of optimizing concrete pavement mixtures in the state of Colorado. This phase included a field investigation of five sites constructed with lower-than-normal cement contents. The mixtures on these projects had a typical 20% replacement with Class F fly ash. The evaluation included an on-site field visit coupled with an information collection of project records.

The evaluation conducted in this phase has revealed that the existing durability of the field sites visited were as expected of any typical concrete paving mixture. The partial replacement of cement with fly ash did not appear to pose any significant deleterious impact to the concrete durability. Although two of the five sections did possess moderate to high distress levels, the structural design is believed to be the predominant factor leading to the observed failures. Furthermore, it is believed that some of the observed distresses could have been prevented or minimized through better control during the construction process: better concrete consolidation during the tie-bar insertion to prevent scarring; and better control of the sawing window to prevent uncontrolled mid-panel cracking.

This project has served to develop the beginning of a knowledge base for concrete pavement durability. Coupled with further evaluation of these pavements via laboratory testing, along with a controlled laboratory testing factorial, additional data can be added to that knowledge base. Integrating the knowledge base with modeling can lead to a concrete mixture optimization system that would allow for rapid identification and proportioning of concrete-making materials.

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Appendix A – CDOT Cost-Benefit Analysis of Projects Completed in FY02

To determine the costs of the material components we contacted the Colorado/Wyoming Chapter of the American Concrete Pavement Association (ACPA). They in turn contacted local suppliers and contractors. This study is based on the following assumed values provided by ACPA:

Portland Cement (Medium Alkali)	\$84 per ton
Class F Fly Ash	\$50 per ton
Year 2000 total PCCP placed	790,000 yd ³

Using these assumptions for the costs of an average paving project, we calculated the cost per cubic yard of the cementitious materials:

Current revision using flexural strength

Portland cement	480 lbs./yd ³
Class F Fly Ash	120 lbs./yd ³
$(480 \text{ lbs./}2000 \text{ lbs.}) \times \$84 + (120 \text{ lbs./}2000 \text{ lbs.}) \times \$50 = \$23.16$	

Concrete with 565 lbs. total cementitious material

Portland cement	452 lbs./yd ³
Class F Fly Ash	113 lbs./yd ³
$(452 \text{ lbs./}2000 \text{ lbs.}) \times \$84 + (113 \text{ lbs./}2000 \text{ lbs.}) \times \$50 = \$21.81$	

To use these values in the context of a typical CDOT paving project we calculate the quantity of concrete that will be used on the unbonded concrete overlay project near Stratton on I-70 that is presently being advertised. This project has 190,600 yd² of 11" PCCP and 15,923 yd² of 12.5" PCCP. This will require 63,768 yd³ of Class P concrete.

Cost of cementitious material according to the current CDOT specifications using flexural strength criteria: $63,768 \text{ yd}^3 \times \$23.16/\text{yd}^3 = \$1,476,867$

Cost of cementitious material if only 565 lbs. total cementitious material is required: $63,768 \text{ yd}^3 \times \$21.81/\text{yd}^3 = \$1,390,780$

If we assume that annual programs will be similar to the Year 2000 paving program of 790,000 yd³, PCCP placed and half of that material would be placed under a specification with flexural strength criteria and a minimum of 565 lbs. total cementitious material, the annual savings will be:

$(790,000 \text{ yd}^3 \times \frac{1}{2}) \times (\$23.16 - \$21.81) = \$533,250$ savings per year or **\$2,666,250** for 5 years.

Appendix B – Photographs of Typical Observations from Field Sites

I-70 near Deer Trail (MP 322.6 to 329.0)

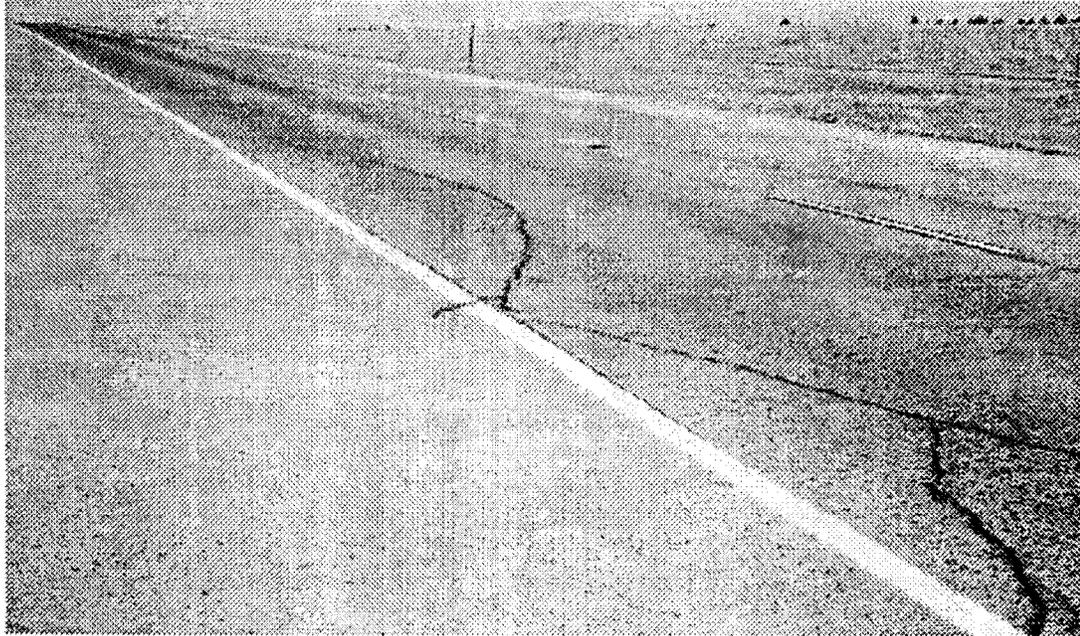


Figure B-1. Longitudinal Cracking of I-70.

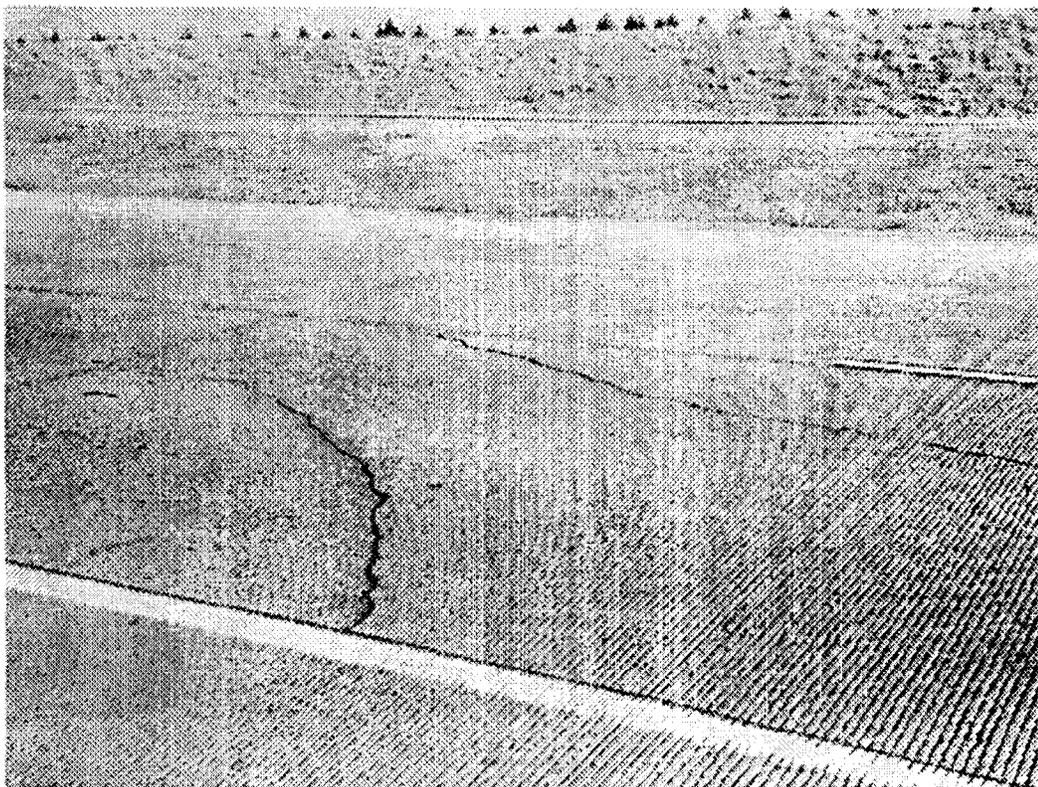


Figure B-2. Longitudinal Cracking of I-70.

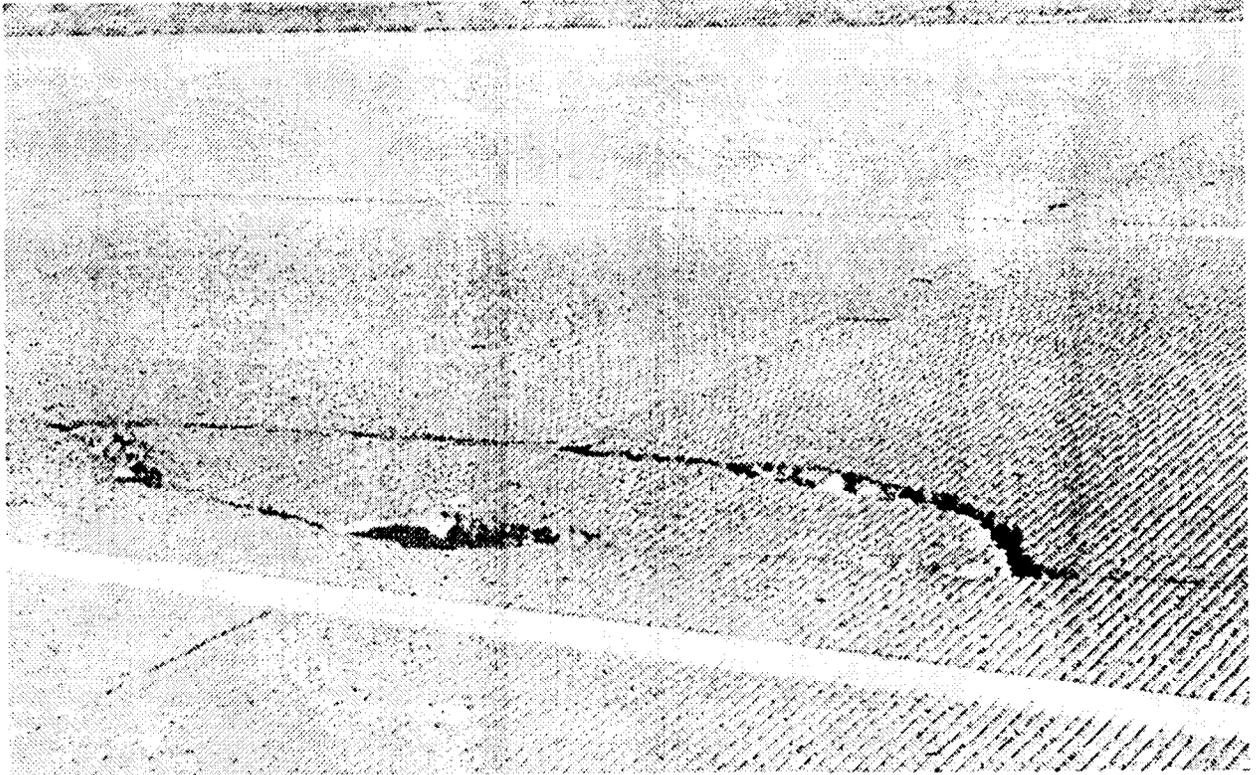


Figure B-3. High Severity Spalling of Cracks on I-70.

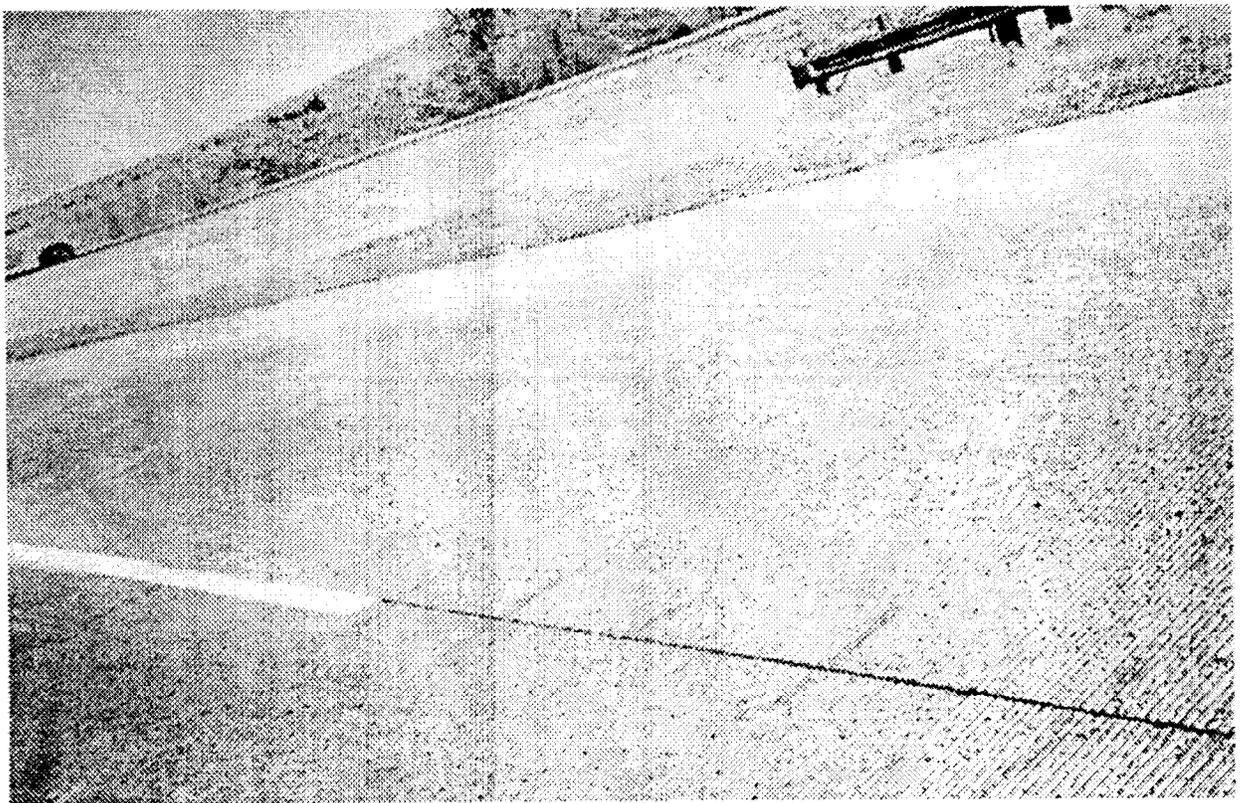


Figure B-4. Tie-Bar "Scarring" on I-70.

I-76 near Barr Lake (MP 23.5 to 31.2)

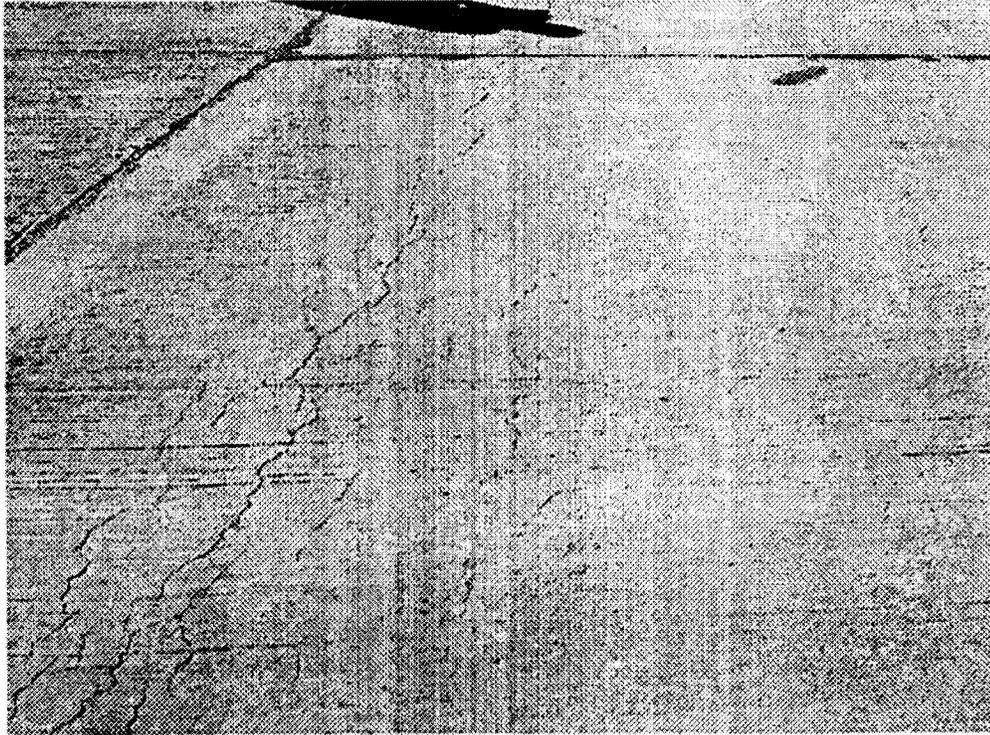


Figure B-5. Possible Fatigue Cracking on I-76 (Western Site).

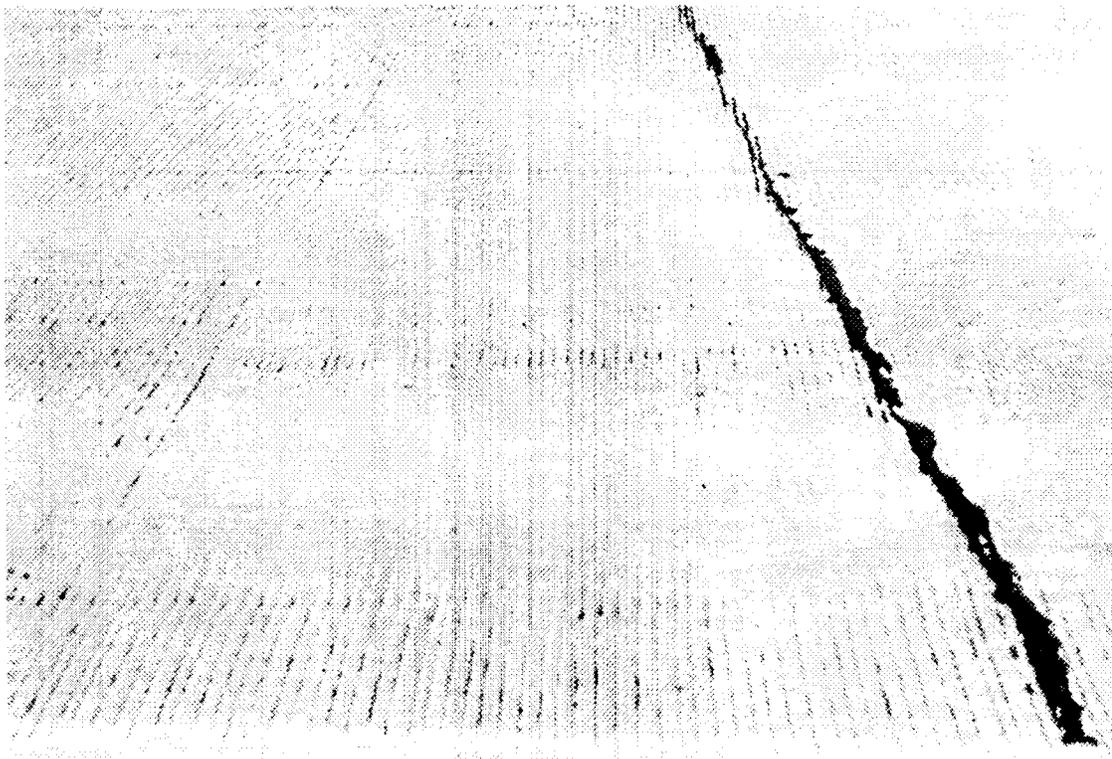


Figure B-6. Surface Polishing on I-76 (Western Site).

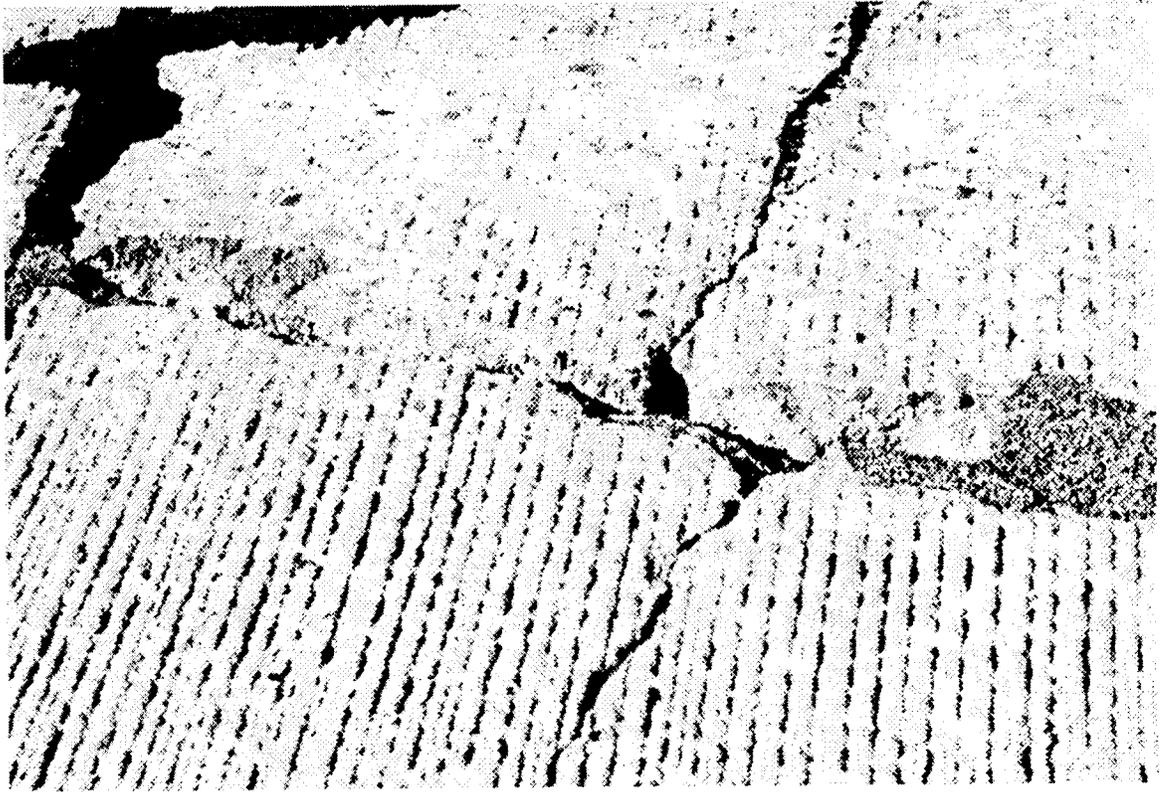


Figure B-7. Severe Spalling on I-76 (Western Site).

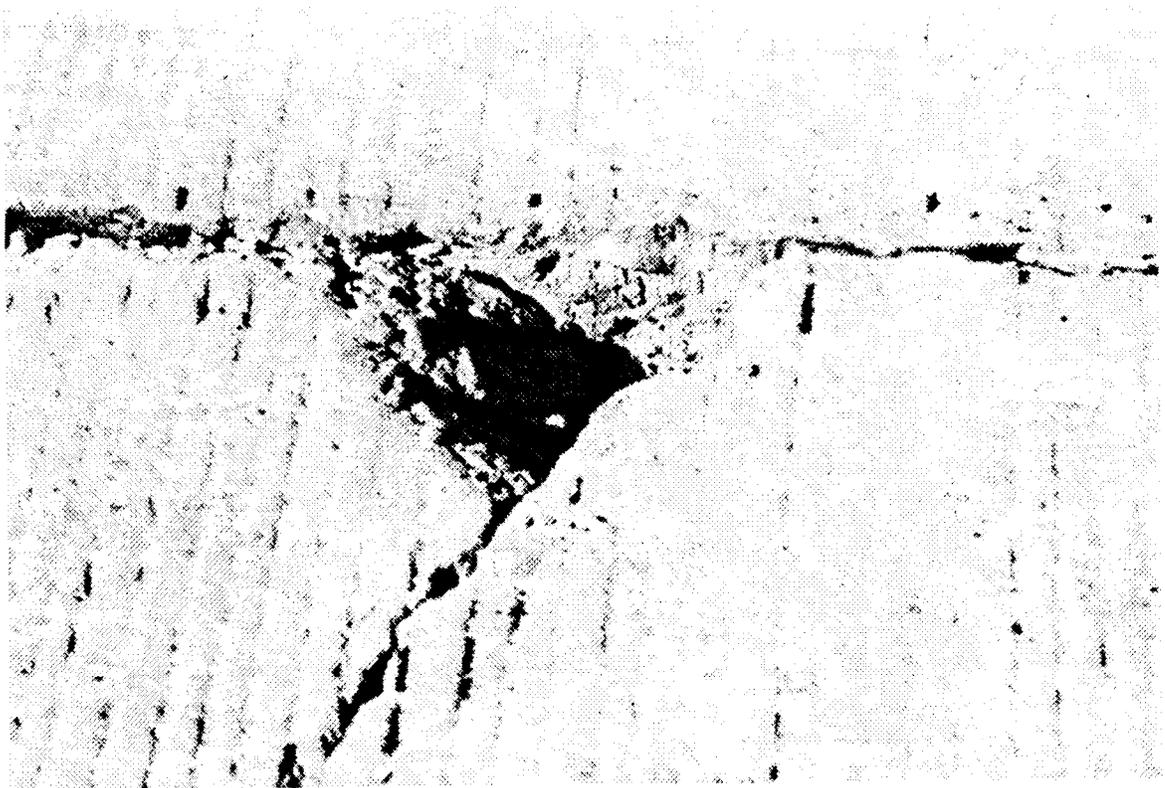


Figure B-8. Severe Spalling on I-76 (Western Site).

I-76 near Roggen (MP 50.1 to 61.9)

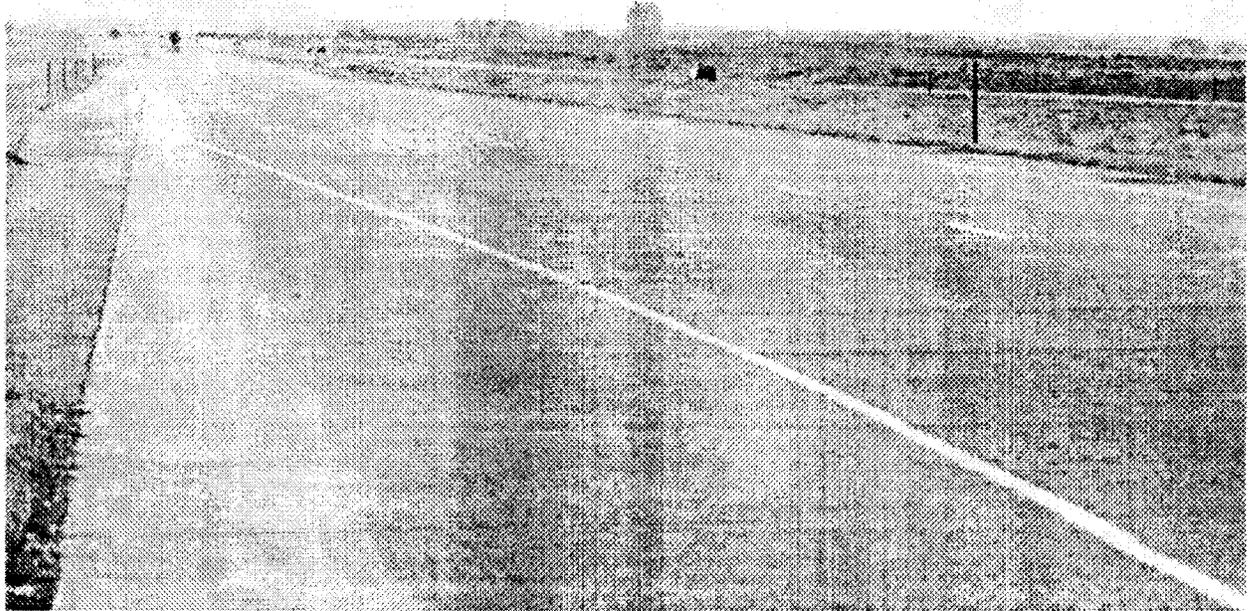


Figure B-9. Good Pavement Condition on I-76 (Eastern Site).

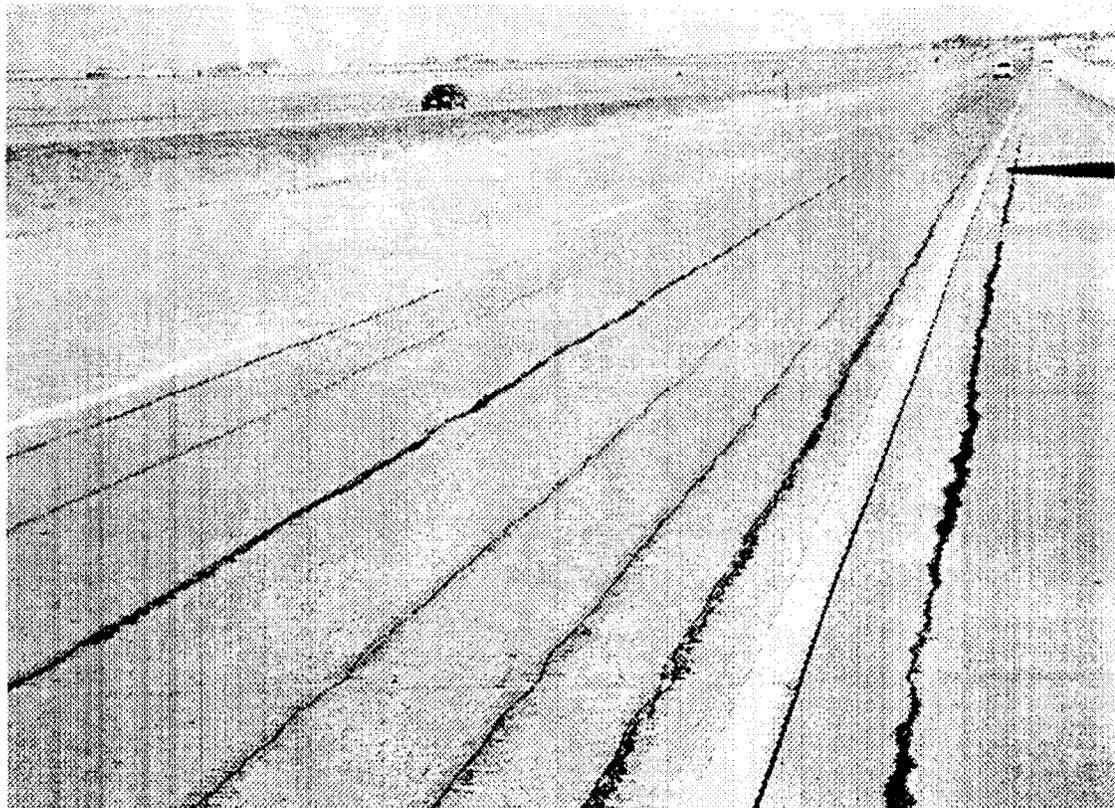


Figure B-10. Traffic Scarring of Pavement Falsely Identified as Longitudinal Cracking by PMS on I-76 (Eastern Site).

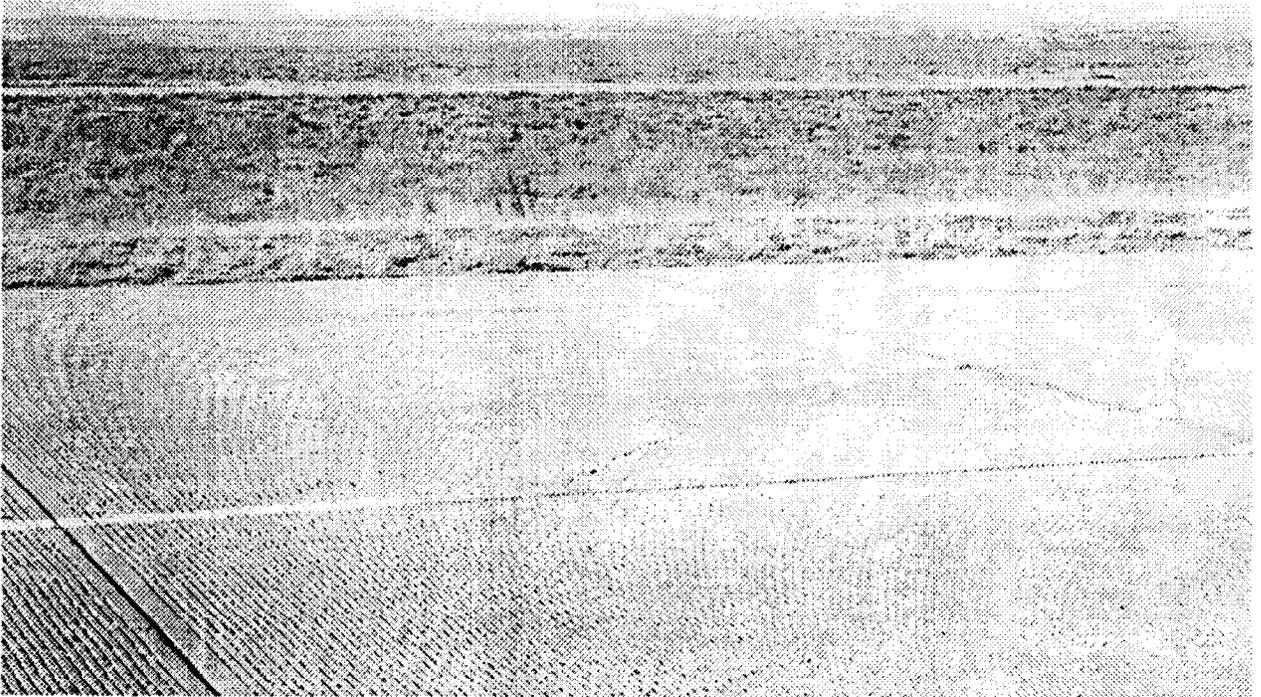


Figure B-11. Occasional Slab Crack on I-76 (Eastern Site).

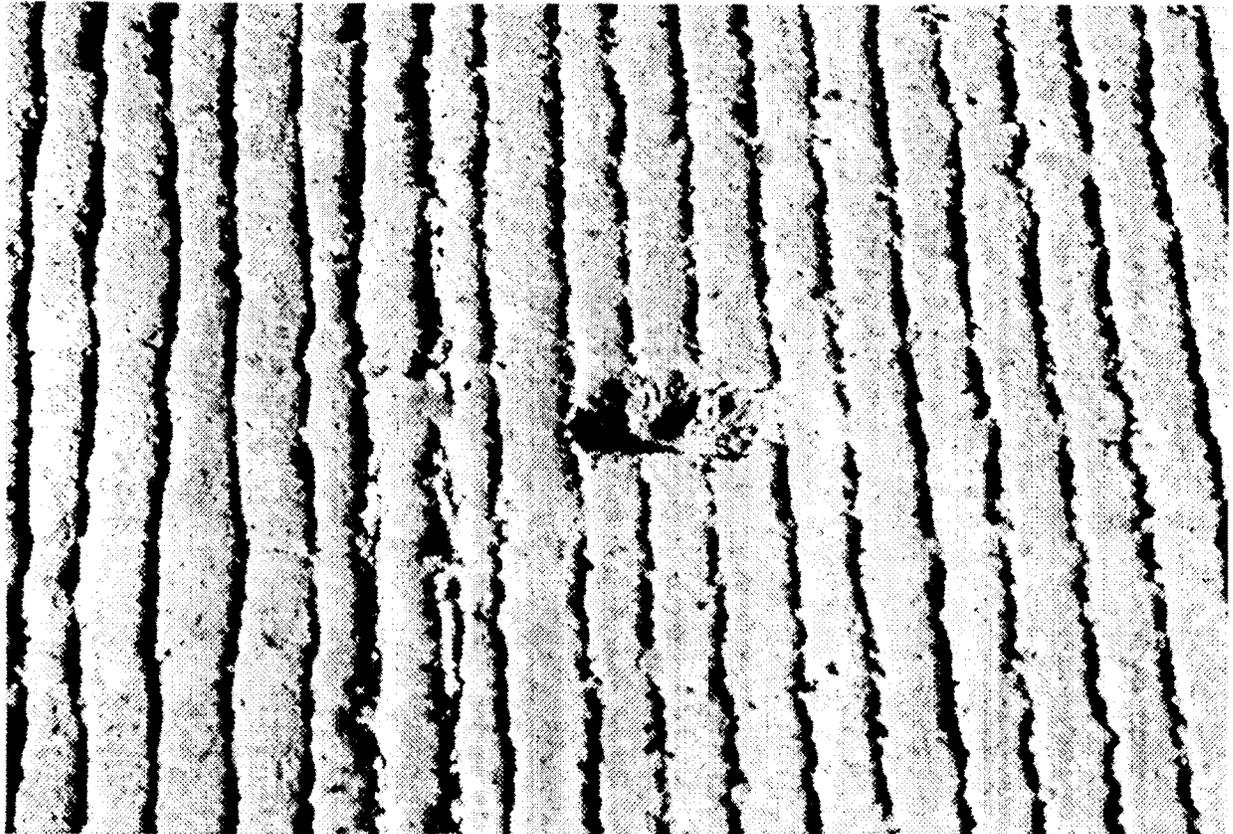


Figure B-12. Occasional Minor Popout on I-76 (Eastern Site).

US 34 east of Greeley (MP 115.2 to 120.0)

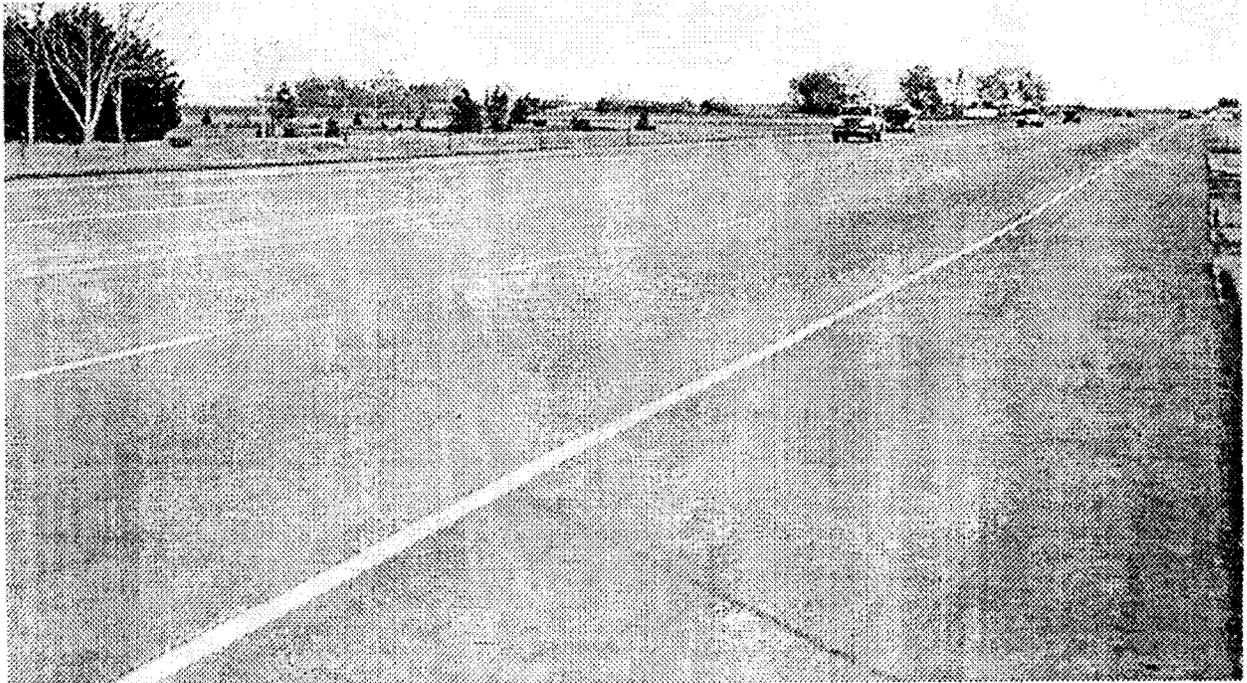


Figure B-13. Good Pavement Condition on US-34.

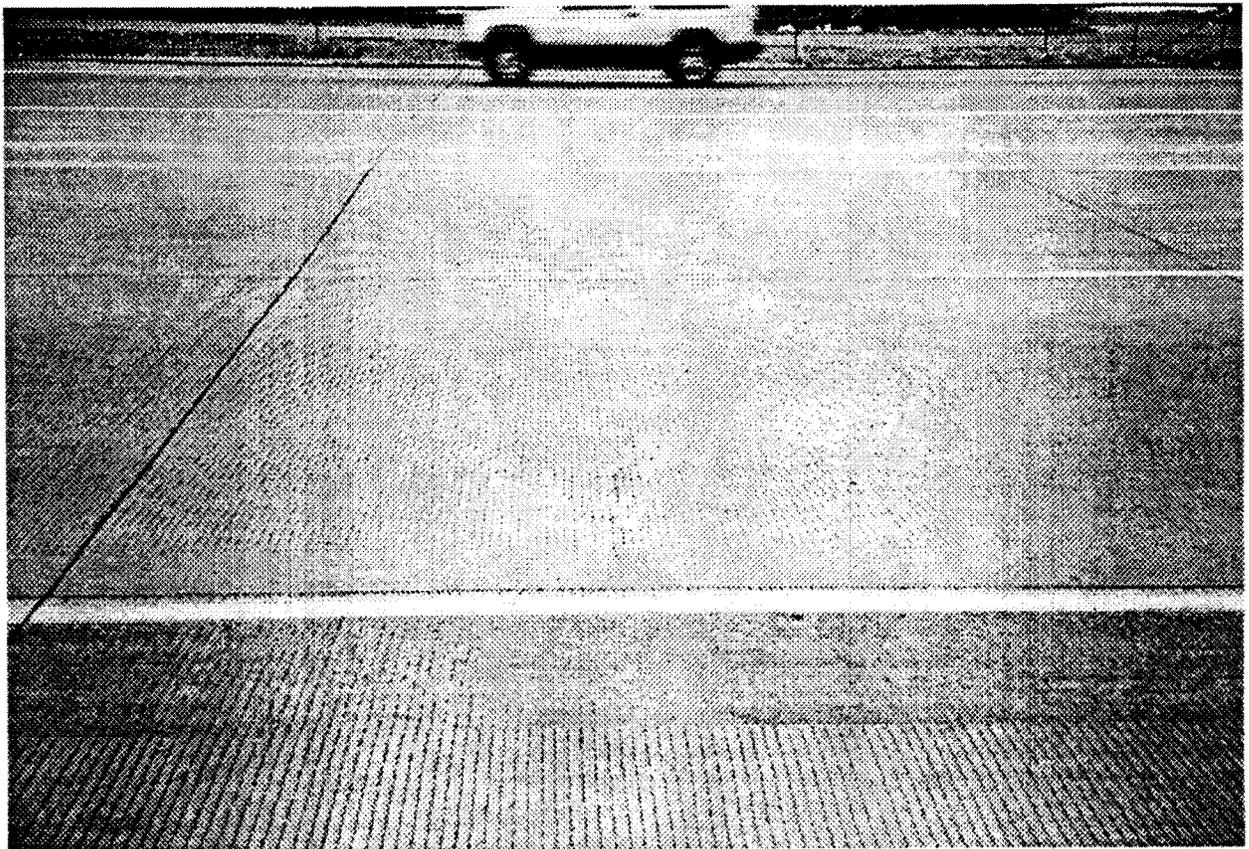


Figure B-14. Localized Mid-Panel Transverse Cracking on US-34.

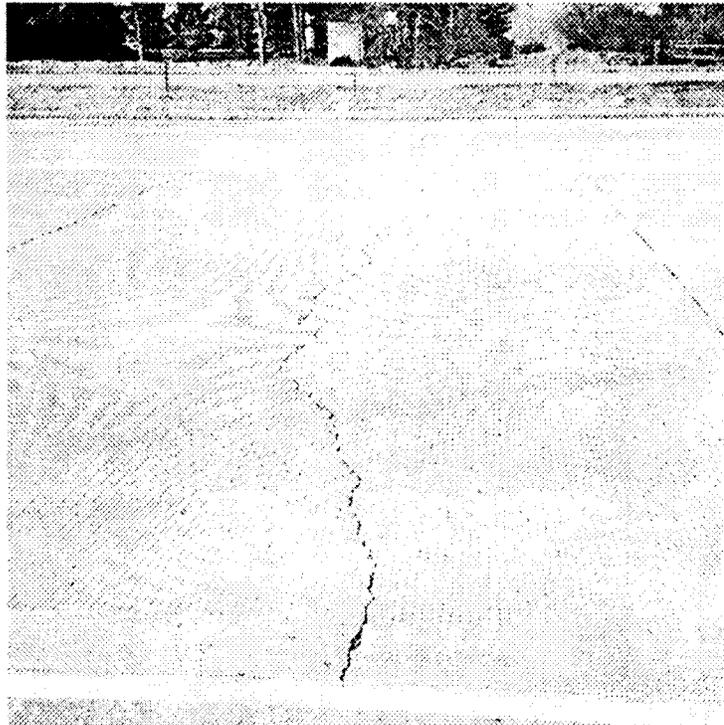


Figure B-15. Localized Mid-Panel Transverse Cracking on US-34.

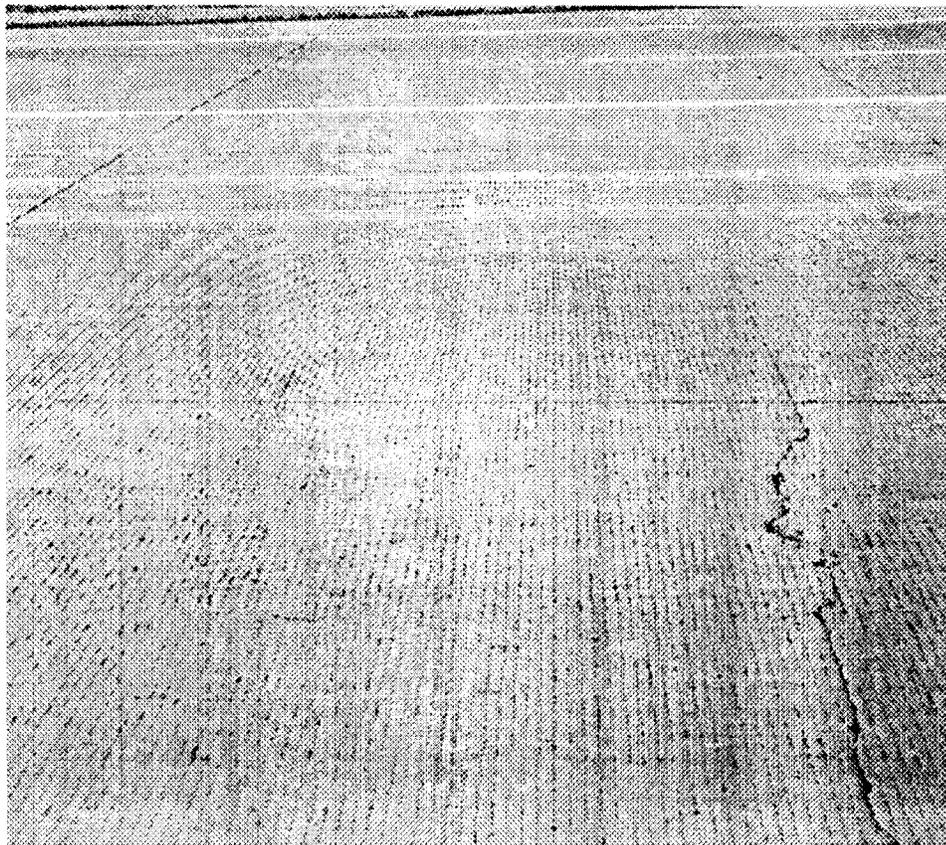


Figure B-16. Mid-Panel Crack and Tie-Bar "Scarring" on US-34.

I-25 Near Johnson Corner (MP 240.2 to 254.2)



Figure B-17. Shattered Slab on I-25.

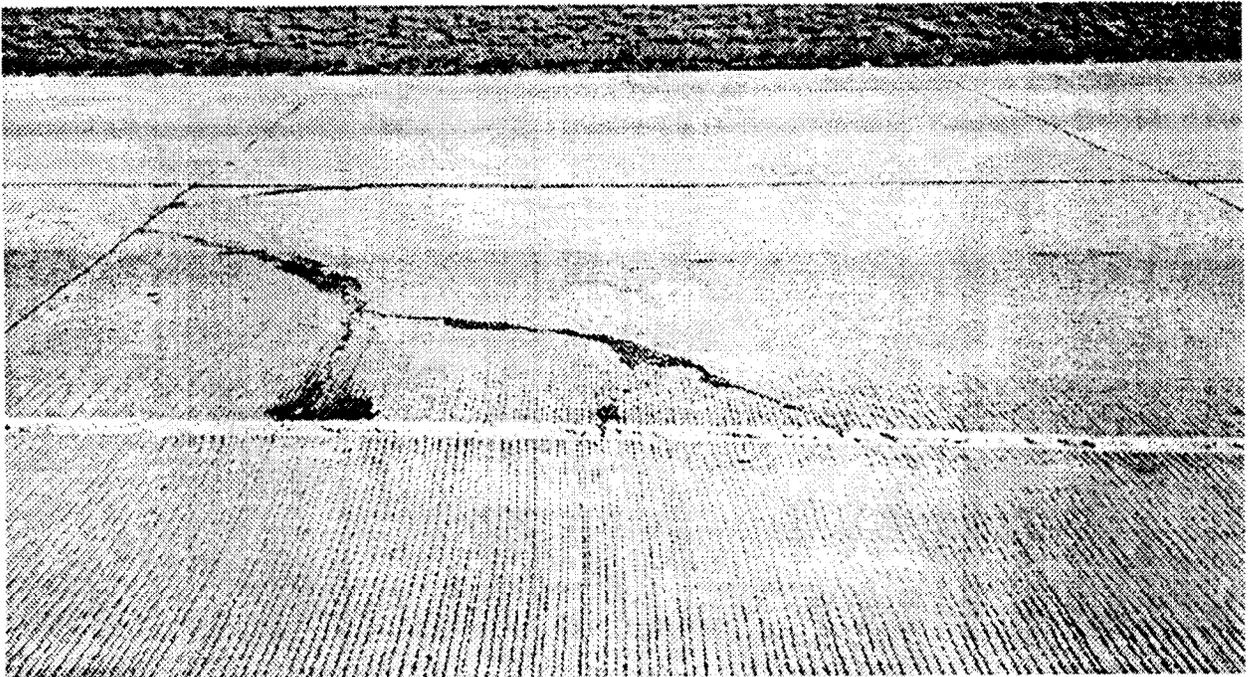


Figure B-18. Shattered Slab on I-25.



Figure B-19. Failing PCC Patch on I-25.

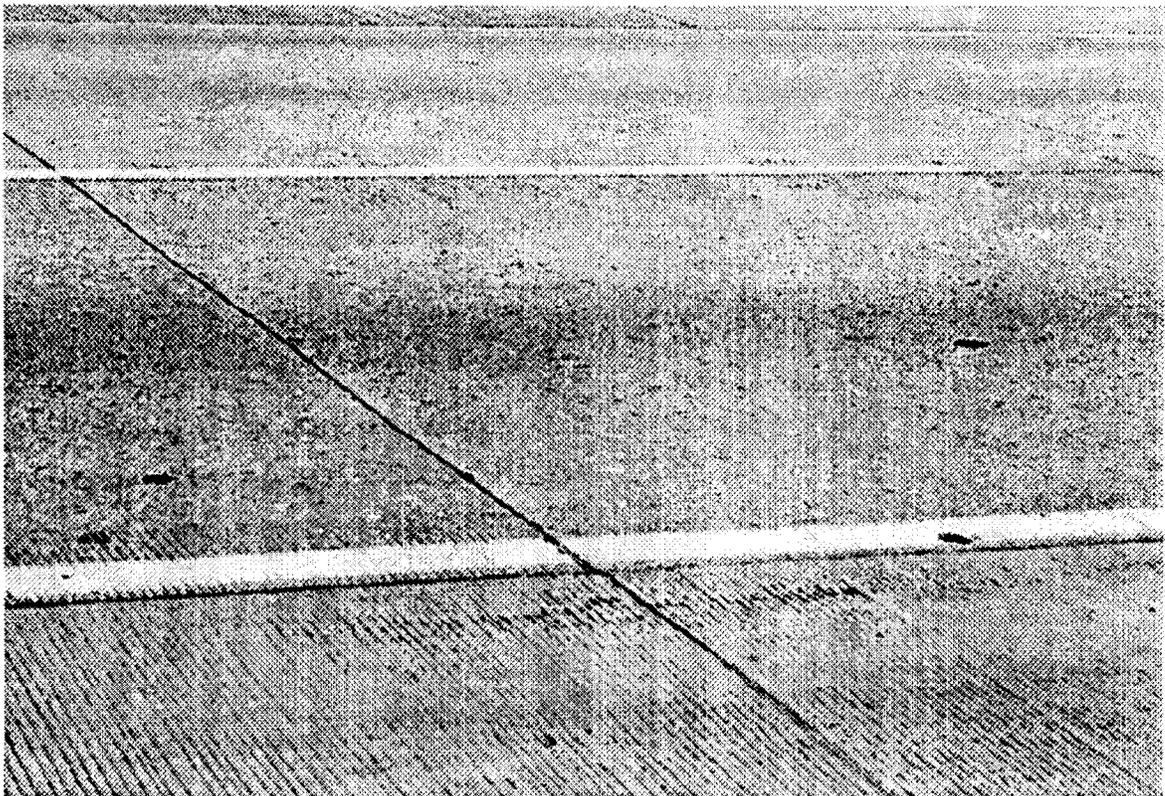


Figure B-20. Surface Polishing on I-25.

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