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Final Report

EVALUATION OF PREMATURE PCCP LONGITUDINAL CRACKING IN COLORADO

Ahmad Ardani
Shamshad Hussain
Robert LaForce

January 2003

COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

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16. Abstract

This report presents an evaluation of several portland cement concrete pavements with premature longitudinal cracking. All of the locations discussed are in Region 1 of the Colorado Department of Transportation (CDOT). Included in this report is an overview of the causes of the premature longitudinal cracking, a description of field and laboratory investigations, and a list of strategies to eliminate such occurrences.

Although there were some isolated cases of differential settlements related to the high swell potential (high PI/lower R-value) of the subgrade soil and/or poor subgrade compaction, this study found the shallow depth of the longitudinal saw-cuts at the shoulder joint to be the main reason for longitudinal cracking. Malfunctioning paver vibrators and unsuitable soils also contributed to the problem. The tests also proved that the wider slab design (14-foot slab) was not a contributing factor.

Implementation: This study resulted in 2 new specifications: 1- Requiring the engineer to measure saw-cut depth at intervals of 1 per 1/10 of a mile (528 ft.). 2- Requiring paving contractors to equip their paving machines with vibrator monitoring devices.

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by

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Report No. CDOT-DTD-R-2003-1

Prepared by
Colorado Department of Transportation
Research Branch

Sponsored by the
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EXECUTIVE SUMMARY

This report presents the results of a research study titled, “Evaluation of Premature PCCP Longitudinal Cracking in Colorado” documenting the investigation of premature longitudinal cracking in several portland cement concrete pavements in Region 1 of the Colorado Department of Transportation (CDOT). Included in this report is an overview of the causes of the premature longitudinal cracking, a list of strategies to eliminate such occurrences, and descriptions of field and laboratory investigations. The evaluation panel first identified possible contributing factors responsible for premature distresses and divided them into two general groups:

Group 1: Cracking with differential settlements related to high swell potential of the subgrade (high PI/lower R-value) and/or poor subgrade compaction.

Group 2: Longitudinal cracking without differential settlement, possibly related to design or construction practices, such as:

- Wider slab design (14’ slabs).
- Shallow saw-cuts of the longitudinal joints at the shoulder.
- Malfunctioning or improper adjustment of the vibrators on the paving machine.

Altogether, three sites with several test sections - all in Region 1- were selected and investigated. The investigation, which was conducted by the research team and the study panel members, included: visual examination and distress survey of the cracked areas, extraction of cores for field and laboratory evaluation, and photographic documentation of the distresses and field work.

Examination of cores from several locations on US-287 and I-70 revealed longitudinal joint saw-cuts that were less than 1/3 of the thickness of pavement, i.e., not deep enough to instigate weakened plane cracking. As a result, longitudinal cracks developed to relieve the internal stresses in the concrete. This discovery eliminated the 14-foot-wide slabs as a possible cause of these longitudinal cracks.

Laboratory testing revealed a definite relationship between improper vibration practices and longitudinal cracking in the path of the vibrators. Cores taken from three different locations on and next to the vibrator trails were sent to Construction Technology Laboratories (CTL) for petrographic analysis. The results showed the air content of the cores taken on the vibrator trails to be consistently lower than the air content of the cores taken next to the vibrator trails. Vibrator frequency set too high and/or prolonged vibration at low paver speed was determined to be the main factor that caused longitudinal cracking along the vibrator trails.

Implementation Statement

Although there were isolated problems related to subgrade soil with high swell potential and poor compaction, this study found two major factors to be responsible for premature longitudinal cracking: inadequate depth of the saw-cut at the shoulder and malfunctioning of vibrators, causing vibrator trails.

This study resulted in the development of two new specifications:

- Requiring the engineer to measure saw-cut depth in intervals of 1 per 1/10 of a mile (528 feet).
- Requiring paving contractors to equip their paving machines with vibrator monitoring devices.

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1.0 INTRODUCTION

Many factors are responsible for premature longitudinal cracking in portland cement concrete pavements. They are primarily improper construction practices, followed by a combination of heavy load repetition and loss of foundation support due to heave caused by frost action and/or swelling soils. This study focused on distresses related to improper construction practices.

Possible construction related causes of premature longitudinal cracking include:

- Time of saw-cutting of the longitudinal joints at the shoulders and centerline.
- Depth of the longitudinal saw-cuts at the shoulder and centerline joints.
- Vibrator trails caused by malfunctioning vibrators on the paver.
- Improperly treated swelling soils with high plasticity index and lower R-value
- Inadequate compaction of the sub base soil.
- Misaligned dowel bars.

Design features such as slab thickness and width, and base/subgrade type and stiffness, strength, and drainage can cause, or have dramatic impact on the severity of, premature longitudinal cracking. In addition, materials properties, including the mix constituents (aggregate type, cement type, admixtures, etc.) and their proportions, may influence longitudinal cracking. Whatever the cause, premature longitudinal cracks have detrimental effects on the overall performance of portland cement concrete pavements. This study determined their causes and recommended ways to prevent or reduce their occurrence in future projects.

2.0 BACKGROUND

The Colorado Department of Transportation's Region 1 has been experiencing premature distresses on some of its concrete pavement primarily in the form of longitudinal cracking. Because of its significant nature, the problem was presented to the Materials Advisory Committee (MAC) for their input and feedback. The MAC recommended establishing a task force to investigate the causes of the longitudinal cracking and to recommend remedial measures. Personnel from CDOT, the Colorado/Wyoming chapter of the American Concrete Paving Association (ACPA), and the paving industry were invited to serve on the task force.

The task force members toured problem areas on I-70 east of Agate, on US-287 south of Kit Carson, and on I-70 west of Deer Trail to evaluate the distresses. The task force reached the consensus that the following could be responsible for these distresses and needed further evaluation:

1. Cracking with differential settlement, attributable to either or both of the following:
    - Unsuitable soils possessing high swelling potential (i.e., high plasticity index/lower R-value).
    - Inadequate compaction of the sub base during construction.
2. Cracking without differential settlement, attributable to improper construction practices or design, caused by one or more of the following mechanisms:
    - Malfunctioning vibrators on the paver, i.e., vibrator frequency set too high causing over-consolidation the concrete mix.
    - Shoulder joint saw-cuts shallower than required by specifications (1/3 of the pavement thickness - D/3 – for 12-foot-wide slabs and 0.4D for 14-foot-wide slabs).
    - Wide (14-foot) slabs.

3.0 OBJECTIVES

The primary objectives of this study were:

1. To identify and confirm the causes of the premature longitudinal cracking observed at several locations in Region 1.
2. To develop strategies to prevent recurrence of the problems.

4.0 DATA ACQUISITION AND ANALYSIS

To accomplish the objectives set forth above, the study panel developed and recommended the following tasks:

- Task 1. Visit locations on I-70 near Agate, on I-70 near Deer Trail, and on US-287 near Kit Carson to identify possible causes of the premature longitudinal cracking.
- Task 2. Conduct field and laboratory investigations of the three sites to confirm the causes responsible for the cracking. The field investigation consisted of extracting cores for visual evaluation and to measure saw-cut depth, and surveying the number of longitudinally cracked slabs as a percentage of the total number of slabs in the project. The laboratory investigation consisted of conducting air-void system analysis on cores taken on and adjacent to the cracks.
- Task 3. Analyze the acquired data.
- Task 4. Develop strategies to minimize or eliminate premature longitudinal cracking in the future.
- Task 5. Prepare a final report to document the entire research project. Include recommendations for the implementation of the results as part of the report.
- Task 6. Present the results of the study to the MAC and the ACPA and request implementation of the recommendations on future highway construction projects.

4.1 Investigation of I -70 Near Agate

Construction for the I-70 Agate Design-Build Project No. 10458 (mp 338.3 to mp 348.15) started in 1998 in the westbound lanes. The eastbound lanes were completed in 1999. During the month of August 2001, distresses, mainly in the form of longitudinal cracks, were encountered at several locations in the westbound lanes (no distresses were reported in the eastbound lanes). The majority of the cracks were scattered between mileposts 340 and 346. Four cracks, each measuring approximately 200 feet in length, and located about four to five feet to the left of the shoulder paint stripe, appeared to be related to improper vibration practices. These cracks are very straight **(Figure 1)** and at a consistent distance from the edge of the pavement.

Figure 1. Premature longitudinal crack on I-70 westbound near Agate.

At some locations near Agate, cracks have developed with substantial differential settlement across the cracks. They tend to wander back and forth between the center of the lane and the right wheel path **(Figure 2).**

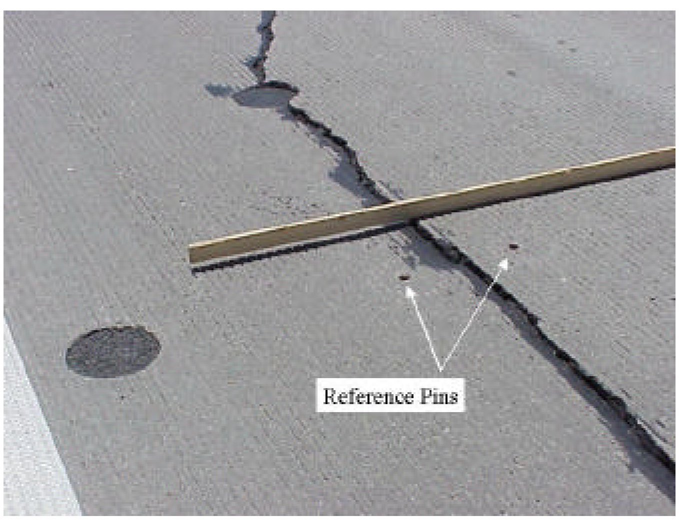


Figure 2. Differential settlement on I-70 westbound near Agate.

These cracks are probably due to under-compaction of the subgrade fill materials or to the high expansive potential of the of highly plastic clayey natural soils in the area (or to the combined effects of both).

The following steps were taken to investigate the causes of these cracks and to attempt to stop their further progression:

1. Pairs of reference pins were installed across the longitudinal cracks.
2. Cores were drilled at the ends of the longitudinal cracks to attempt to stop their progression.
3. Steel rebar stitches were installed across a crack to prevent further movement.
4. Cores were drilled on the longitudinal cracks to investigate the concrete.
5. Undisturbed soil samples of the subgrade natural soils were obtained.
6. The cracks were sealed by CDOT Maintenance.

Figure 3. Reference pins installed across a joint.

Early in 2001, pairs of steel reference pins (**Figures 2 & 3)** were installed on either side of the longitudinal cracks to provide permanent reference points for monitoring changes in the crack widths and the differential settlement across the crack. Pins were installed at MP's 340.260, 340.453, 340.529, 340.751, 340.891, 341.059, 342.504, and 345.275. The crack widths were measured at 1-2 month intervals. The results are shown in Appendix A.

During the spring of 2001, core holes were drilled at each end of the cracks in an attempt to prevent further progression. However, several months later, at some locations, the cracks were observed to have propagated several feet beyond the core holes. The crack propagation beyond the core holes was mainly in the direction of traffic (to the west) and mostly at locations where substantial differential settlement had occurred.

During October of 2002, the Region 1 Limon Residency arranged to cross-stitch the cracks between MP 346 and 340. At 18-inch intervals, on alternate sides of the crack, holes were drilled through the concrete at about a 45º angle to the surface of the pavement so they crossed the crack near the middle of the concrete depth **(Figure 4)**. Twenty-inch-long pieces of 5/8-inch steel rebar were coated with epoxy cement and driven through the concrete into the base. The ends of the bar were driven below the surface of the pavement and the holes sealed with epoxy cement. The performance of the cross stitches is being monitored.

Figure 4. Installation of stitches on I-70 at Agate.

During October 2001, Region 1 Materials, with the help of its drilling crew and CDOT maintenance personnel from Limon, extracted numerous cores between mileposts 340.0 and 348.0. The cores were extracted on and next to longitudinal cracks believed to have been caused by a malfunctioning vibrator with the intention of investigating the concrete paste and the orientation of the aggregate particles in comparison with cores taken from adjacent locations where cracks had not developed. Cores were also taken from the adjoining shoulder slabs.

Undisturbed soil samples were taken in the Agate area where the concrete pavement had undergone differential settlement. The soil samples were sent to the CDOT Central Laboratory for testing. These test results confirmed the results of the previous soil survey and laboratory tests. The soil plasticity and the swelling potential are high (PI = 30-39) and fraction passing No. 200 sieve is very close to 100 %. The test results are shown in Appendix B. Soils having that much swelling potential are very sensitive to moisture change and can undergo substantial movement with moisture penetration.

Cracks help surface water penetrate into the subgrade natural soils where it becomes a source for soil swelling and freeze-thaw action resulting in slab movement. That movement promotes cracking begun due to other types of distresses. Region 1 Maintenance sealed the cracks to help prevent further water penetration into the subgrade.

4.2 Investigation of US-287 at Kit Carson

US-287, south of Kit Carson, was a 9-mile-long project built in 1998. The two-lane concrete pavement has 14-foot-wide slabs and is 9 inches thick with the shoulder thickness tapered from 9 inches at the shoulder joint to 5 inches at the outside edge of the pavement. At the approaches to structures the shoulders are full depth. Both lanes were paved monolithically from north to south.

The longitudinal cracks on US-287 were assumed to be due to shallow saw-cut depth at the shoulder joint or to vibrator trails created by malfunctioning paver vibrators. Both factors were found to have contributed to the cracking. It should be noted that a total of only 0.30 percent of the slabs in the 9-mile-long project were cracked.

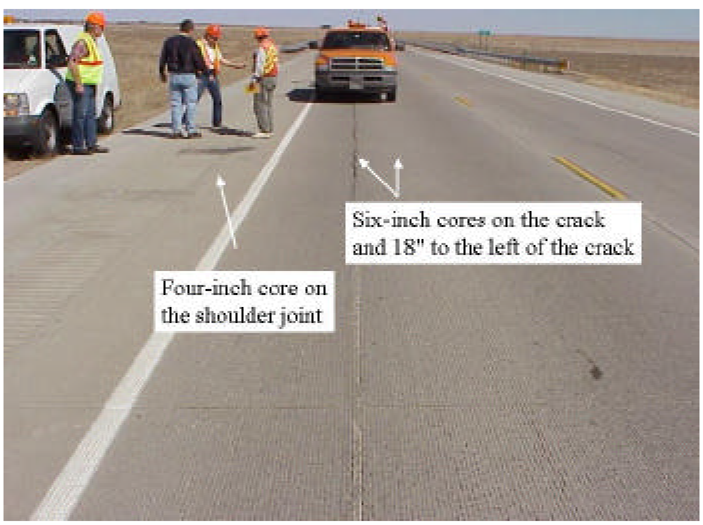


Figure 5. Core locations on the vibrator trail - US-287 southbound.

A set of three core samples was taken at each of three different locations southbound through the project. A set consisted of a six-inch core on the longitudinal crack, a six-inch core about 18 inches to the left of the first core, and a four-inch core on the shoulder joint **(Figure 5)**. The six-inch cores were sent to Construction Technology Laboratories (CTL) for petrographic analysis; the four-inch cores were used to determine if the shoulder joint had cracked through, as it should **(Figure 6)**.

The results of CTL's testing showed the air content of the six-inch cores taken on the vibrator trails to be consistently lower than the air content of the cores taken from the center of the lane. This proved that vibrator operation at too high frequency or prolonged vibration at low paver speed was the main cause of the vibrator trails. (For a complete analysis of the air-void system refer to Appendix C.)

Figure 6. Cores from US-287 southbound.

Figure 7. Wandering cracks in the northbound lane of US-287.

Examination of the four-inch cores taken on the shoulder joint revealed that the saw-cuts were not deep enough (less than 0.4 D for 14-foot slabs) to instigate a weakened plane. As a result, longitudinal cracks developed in the travel lanes to release the strength gain of the concrete.

An overactive vibrator apparently created a vibrator trail which caused a weakened plane in the concrete. In some areas, longitudinal cracks developed along the vibrator trail even where the shoulder joint was working, i.e., the saw-cut was at a proper depth and the joint had cracked through.

Split tensile strength tests were performed on 6-inch-diameter cores extracted from the vibrator trail where the tining tracks were deeper, but no longitudinal crack was evident – see the foreground of Figure 5. Split tensile strength tests were also conducted on cores taken next to the vibrator trails **(Figure 6)**. The main purpose was to determine if the cores taken from the vibrator trials showed lower strength than cores taken next to them. This investigation was inconclusive. The results are shown in Table 1.

The southbound cracks occurred primarily in the vibrator trail and are a consistent distance from the edge of the pavement **(Figure 5)**. In contrast, while most of the longitudinal cracks in the northbound lanes are in the right wheel path, they wander from side to side **(Figure 7)**.

Table 1. Split tensile strength comparison (psi), US-287.

Vibrator Trail Path	Between the Trails
585	630
650	645
670	535
550	570
614 (Average)	595 (Average)

4.3 Investigation of I-70 at Deer Trail

In April of 2002, CDOT's Research Branch, with the help of Maintenance Patrol 16 from Deer Trail, extracted 4 cores from the longitudinal shoulder joint on I-70 eastbound near Deer Trail between Mileposts 326-327 **(Figure 8)**. The slab width in the driving lane, unlike those investigated previously on US-287 (14-foot slabs), was standard 12 feet. The longitudinal cracks at this location consistently began at the shoulder joint and wandered diagonally through the wheel path to about mid-

Figure 8. Longitudinal cracks on 12' wide slabs - I-70 at Deer Trail.

slab. Cracks were also noted on the shoulder parallel to the joint. I-70 at this location was built in 1987 with lower cement content (565 lb. total cementitious, including 455 lb. of cement and 110 lb. of fly ash) and with skewed transverse joints on 18’ spacing.

Figure 9. Cores from the non-working shoulder joint on I-70 at Deer Trail.

As shown in **Figure 9**, none of the saw-cuts at the shoulder joint were working. The pavement depth was 10.25 inches; the saw-cut measured between 2 and 2.25 inches (35% shallower than D/3). This proves, once more, that the longitudinal cracks are due to shallow saw-cut depth at the shoulder joint.

5.0 CONCLUSIONS AND RECOMENDATIONS

The conclusions and recommendations presented here are based on the results of visual observations and field and laboratory investigations of several concrete pavements in Region 1 of CDOT. CDOT, ACPA and the concrete paving industry conducted this study as a joint effort.

5.1 Conclusions

- Untreated native soil with high swelling potential i.e., high plasticity index (PI), lower resistance to lateral movement (lower R-value) and poor compaction were identified as two main contributing factors in the development of premature longitudinal cracking. These types of distresses manifest themselves in the form of longitudinal cracks with differential settlements.
- The majority of the longitudinal cracks were attributed to a shallow saw-cut at the shoulder joints. In some cases the saw-cuts were only 50 percent of the recommended depth. CDOT requires D/3 for standard 12-foot lanes and 0.4D for wider slabs (0.4D mimics the European specification for concrete pavements wider than 12 feet).
- This study found that the 14-foot-wide slab design was not among the causes of longitudinal cracking. CDOT adopted the14-foot slab design in 1996 based on the results of the LTPP SPS-2 experiment, and a supplemental study conducted by Dr. Michael Darter of ERES. The wider slab design is highly recommended for rural highways.
- This study also proved that malfunctioning or improperly adjusted paver vibrators could promote premature longitudinal cracking. Vibrators working at too high frequencies over-consolidate the concrete mix causing non-uniform dispersion of the aggregate and forming vibrator trails. Laboratory investigation of cores extracted on and adjacent to the vibrator trails clearly confirmed this phenomenon. The cores obtained on the vibrator trails had consistently lower air content than cores obtained 18 inches away - in the center of the lane.

5.2 Recommendations

- Premature longitudinal cracking due to improper depth of the longitudinal saw-cut can be prevented by adhering to CDOT's present specification, which requires saw-cut depth of

D/3 for 12-foot slabs and 0.4D for 14-foot slabs. It is recommended that project engineers in the field measure saw-cut depth at intervals of 1 per 1/10 of a mile (528 feet). This specification has already been incorporated into CDOT's Field Materials Manual.

- It is strongly recommended that the paving contractors equip their paving machines with frequency monitoring devices for the vibrators. These monitoring devices provide the transportation agencies and the paving contractor a necessary tool to help achieve a quality concrete pavement that is long-lasting. CDOT recommends following Iowa DOT's specification for monitoring the frequencies of the vibrators. CDOT is in the process of fine-tuning Iowa's specification and plans to implement the results in the near future.
- Accurately recognizing and predicting the potential volume change of expansive soils and their treatment prior to construction plays a major role in overall longevity and performance of pavements. It is necessary to alleviate or eliminate the detrimental effects of expansive soils.

Appendix A

MOVEMENT PINS READINGS (I-70 Agate)

	Horizontal Movement (in)				Vertical Movement (in)							
	12-21-01	02-27-02	06-24-02	11-14-02	12-21-01		02-27-02		06-24-02		11-14-02*	
MP					L	R	L	R	L	R	L	R
340.260	0.000	0.000	0.000	0.000	0.00	0.00	-0.48	-0.36	0.00	0.00	0.240	0.12
340.453	0.000	0.000	0.063	0.125	-0.24	-0.12	-0.60	-0.36	-0.24	0.00	-0.36	-0.12
340.529	0.063	0.063	0.063	0.063	-0.12	0.00	+0.96	+1.32	0.00	+0.12	0.0	0.0
340.751	0.000	0.000	0.000	0.000	-0.24	-0.12	-0.36	-0.24	-0.36	-0.36	-0.12	-0.12
340.891	0.000	0.000	0.000	0.000	-0.60	-0.12	+1.20	+1.56	+0.60	+0.96	0.48	0.96
341.059	0.000	0.000	0.063	0.063	0.00	-0.48	-0.12	0.00	0.00	0.00	0.12	0.12
342.504	0.000	0.000	0.000	0.000	0.00	+0.12	---	---	+0.12	+0.12	0.24	0.36
345.275	0.125	0.125	0.313	0.250	-0.72	+0.12	-0.12	+0.36	+0.24	+0.60	0.48	0.72

L: Pin installed on the north side of the crack (shoulder side)
R: Pin installed on the south side of the crack (median side)
* The readings were taken approximately one month after the stitching of the longitudinal cracks.

Appendix B

Colorado Department of Transportation
Report Form #323

Project ID	13165	**Location**	Kit Carson to I-70 - SH 59		
Project	STA 059A - 027	**Source**	DRIVE SAMPLE	**Report Date**	12/18/2001
F.S. #	128949	**Region**	01	**Construction**	3200

Engineer Tim Aschenbrener - Matls./Geotech. Sect. Engr.

Comments Drive Sample -- Run at 250 psf
Sample Sent to GEC

Test #	Lab #	SP?	Station	Depth	LL	PL	PI	R-Val	Group Class(GI)	mr
1	2001-0914	None	MP 340.442	14.0"	44	14	30		A-7-6(16)	

Gradations:

mm	75	25	19	9.5	#4	#10	#40	#200
in	3	1	3/4	3/8				
%Pass				100	88	86	81	64
As Run				100	88	86	81	64

Lab Performing Work:

Atterberg:	Gnd. Eng.	T180:	
Direct Shear:		Mechanical Analysis:	Gnd. Eng.
R-Value:		Other:	Gnd. Eng.
T99:			

Test #	Lab #	SP?	Station	Depth	LL	PL	PI	R-Val	Group Class(GI)	mr
1	2001-1092	None	MP 340.442	2.5'	58	19	39		A-7-6(43)	

Gradations:

mm	75	25	19	9.5	#4	#10	#40	#200
in	3	1	3/4	3/8				
%Pass							100	99
As Run							100	99

Lab Performing Work:

Atterberg:	Gnd. Eng.	T180:	
Direct Shear:		Mechanical Analysis:	Gnd. Eng.
R-Value:		Other:	Gnd. Eng.
T99:			

Key

LL = Liquid Limit (AASHTO T89)
PL = Plastic Limit (AASHTO T90)
PI = Plastic Index (AASHTO T90)
SP? = Meets special provision requirements?
R Val = Stab R-Value (CPL3101)
mr = Resilient Modulus (psi)
GI = Group Index

GROUND
ENGINEERING CONSULTANTS

Project	CDOT Soils Testing	*Date*	December 4, 2001
Job Number	**00-1084**		
Reported to	Colorado Department of Transportation Materials and Geotechnical Section 4201 E. Arkansas Ave. Denver, CO 80222 Attn: Paul Lane	*Report Number*	

Sample Information

Field Sheet Number 128949

Sample Number 2001-0914 Retest @ 14"

Particle Size Analysis (AASHTO T 88)

Sieve Size	Percent Passing
3/4"	100.0
1/2"	100.0
3/8"	100.0
#4	87.5
#10	85.7
#16	84.4
#40	80.9
#50	79.1
#100	71.3
#200	64.0

Atterberg Limits (AASHTO T 89 & T90)

Liquid Limit 44

Plasticity Index 30

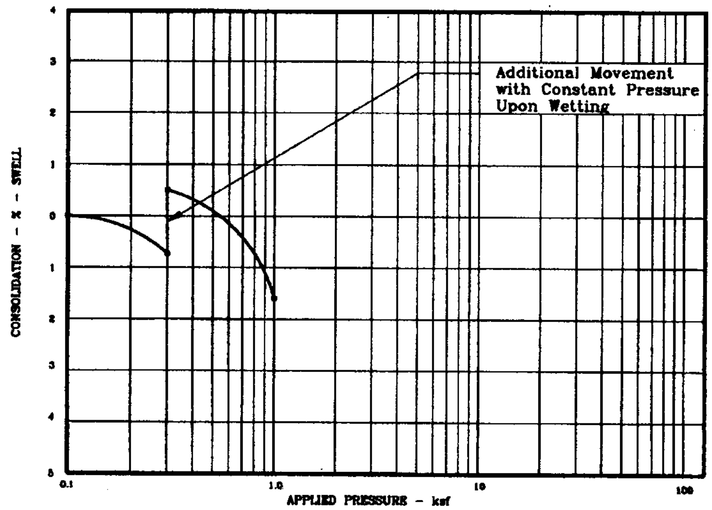
Classifications

ASSHTO Classification (AASHTO M 145)	A-7-6(16)
Unified Classification (ASTM D 2487)	Sandy Lean Clay (CL)
Soluble Sulfate Content	0.19%
Swell Potential	1.24%
As received moisture (AASHTO T 265)	17.1%
As received dry density (pcf)	114.0

GROUND Engineering Consultants

By: ______________________

7393 Dahlia Street, Commerce City, CO, 80022-1834
Phone (303) 289-1989 Fax (303) 289-1686



Liquid Limit = 44
Plasticity Index = 30
Percent Passing No. 200 Sieve = 64.0

Swell Protential: 1.24 percent

Moisture Content = 17.1 percent

Dry Unit Weight = 114.0 pcf

Sample of: Sandy Lean Clay; A-7-6(16)

From: Field Sheet No. 128949
Lab ID 2001-0914 Retest @14"

GROUND ENGINEERING CONSULTANTS

SWELL-CONSOLIDATION TEST RESULTS

JOB NO. 00-1064	DRAWN BY: HS
FIGURE: –	APPROVED BY: MQ
CADFILE NAME: 1064SWL02.DWG	

GROUND
ENGINEERING CONSULTANTS

Project	CDOT Soils Testing	*Date*	December 4, 2001
Job Number	**00-1084**		

Reported to Colorado Department of Transportation
Materials and Geotechnical Section
4201 E. Arkansas Ave.
Denver, CO 80222

Report Number

Attn: Paul Lane

Sample Information

Field Sheet Number 128949
Sample Number 2001-1092 Test @ 2.5 ft.

Particle Size Analysis (AASHTO T 88)

Sieve Size	Percent Passing
3/4"	100.0
1/2"	100.0
3/8"	100.0
#4	100.0
#10	100.0
#16	100.0
#40	100.0
#50	99.5
#100	99.1
#200	98.5

Atterberg Limits (AASHTO T 89 & T90)

Liquid Limit 58

Plasticity Index 39

Classifications

ASSHTO Classification (AASHTO M 145)	A-7-6(43)
Unified Classification (ASTM D 2487)	Fat Clay (CH)
Soluble Sulfate Content	BDL*
Swell Potential	4.44%
As received moisture (AASHTO T 265)	25.9%
As received dry density (pcf)	98.8

*Below Detectable Limits

GROUND Engineering Consultants
By: ____________________

7393 Dahlia Street, Commerce City, CO, 80022-1834
Phone (303) 289-1989 Fax (303) 289-1686

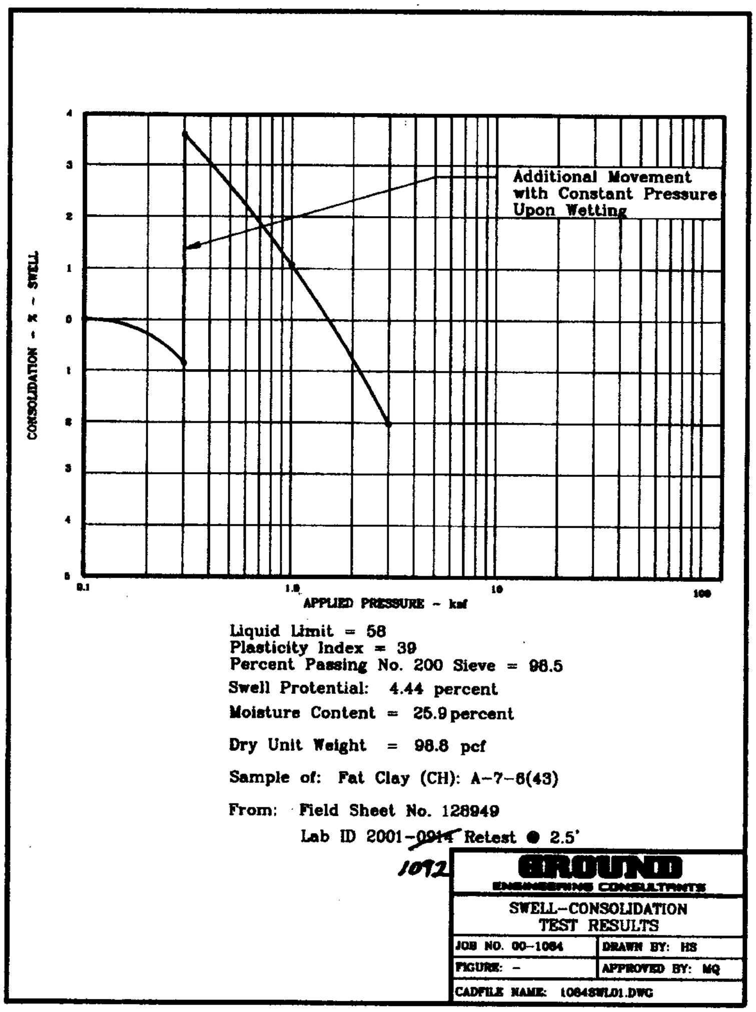

Additional Movement with Constant Pressure Upon Wetting
CONSOLIDATION - % - SWELL
APPLIED PRESSURE - ksf
Liquid Limit = 58
Plasticity Index = 39
Percent Passing No. 200 Sieve = 98.5
Swell Protential: 4.44 percent
Moisture Content = 25.9 percent
Dry Unit Weight = 98.8 pcf
Sample of: Fat Clay (CH): A-7-6(43)
From: Field Sheet No. 128949
Lab ID 2001-~~0914~~ 1092 Retest ● 2.5'
GROUND
ENGINEERING CONSULTANTS
SWELL-CONSOLIDATION
TEST RESULTS
JOB NO. 00-1064
DRAWN BY: HS
FIGURE: -
APPROVED BY: MQ
CADFILE NAME: 1064SWL01.DWG

Figure 10

Appendix C

CTL
Construction Technology Laboratories, Inc.

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Skokie, Illinois 60077
847 965 7500
Fax 847 965 6541
www.CTLGroup.com

PETROGRAPHIC SERVICES REPORT

CTL Project No.: 151817 *Date*: May 7, 2002

Re: Air-Void System Analysis of Concrete Cores from Pavements, US 287, Colorado

Six concrete cores, labeled 1 and 3 STA 14+000, 4 and 6 STA 10+600, and 9 and 10 STA 0+400 (Figs 1-3) were received April 11, 2002 from Mr. Ahmad Ardani, Colorado Department of Transportation, Research Branch, Denver, Colorado. Reportedly, the cores were taken from three different locations because of concern that vibrator problems resulted in longitudinal cracking in the pavements. Mr. Ardani requested air-void system analysis on these cores to evaluate and compare air-void systems.

FINDINGS AND CONCLUSIONS

The results of the air-void system analysis are summarized below; additional details of which are presented in the attached air-void data sheets and photomicrographs

1. The concrete cores are air entrained, based on 1) the presence of small, spherical voids and 2) the measured air-void parameters (Figs. 4-9).
2. Air content is consistently lower in the cracked cores compared to the un-cracked companion core High frequency vibration or prolonged vibration can decrease air content.
3. The air-void system is consistently finer in the cracked cores compared to the un-cracked companion core Vibration by design releases entrapped voids and thereby reducing the average size of the air voids (specific surface).
4. There is no consistency in air-void spacing between cracked and un-cracked cores. In the three comparisons between cracked and un-cracked cores, one spacing factor is the same, one is higher and one is lower. This feature is not unusual, vibration can have little effect on air-void spacing factor

METHODS OF TEST

Air-void system analysis was performed in accordance with the modified point-count method of ASTM C 457-98, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." The cores were cut longitudinally and one of the resulting surfaces of each was finely lapped (polished) and analyzed using a computerized apparatus.

David B. Vollmer
Senior Petrographer
Petrographic Services

DBV

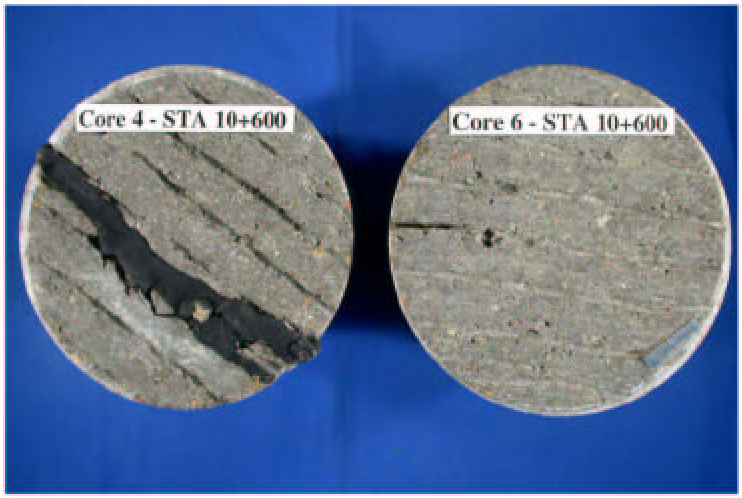
151817

Attachments

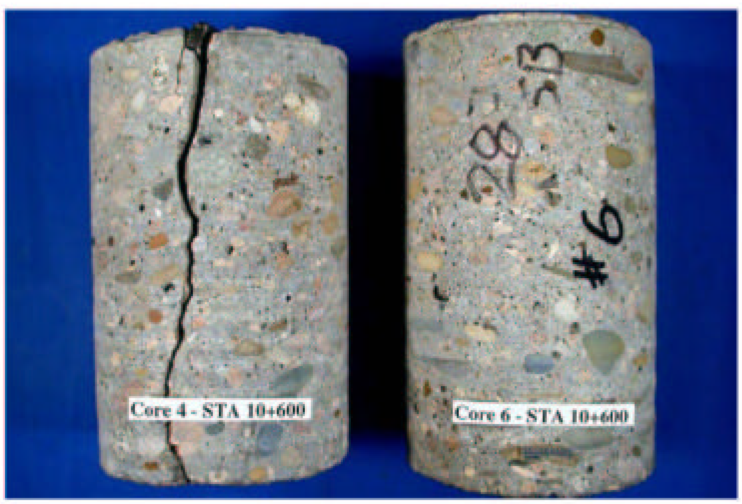
1a. Top surface.

1b. Side view.

Fig. 1 (a & b) Concrete Cores 1 and 3, as received for analysis. Core 1 is from the cracked potion of the pavement and Core 3 is from the center of the lane.

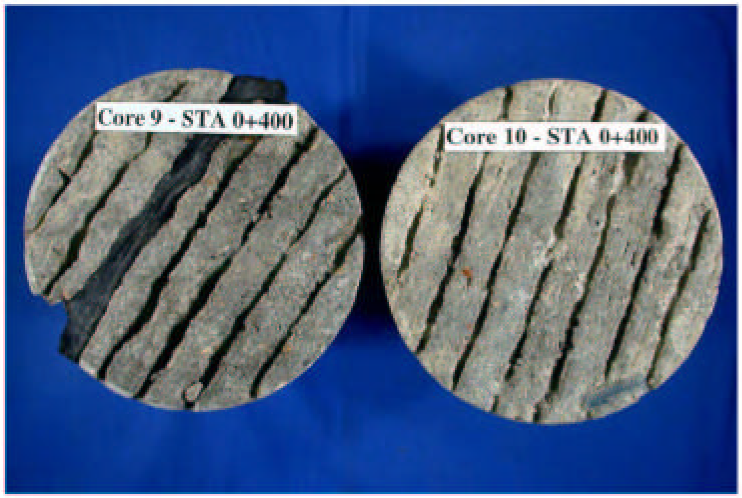


2a. Top surface.

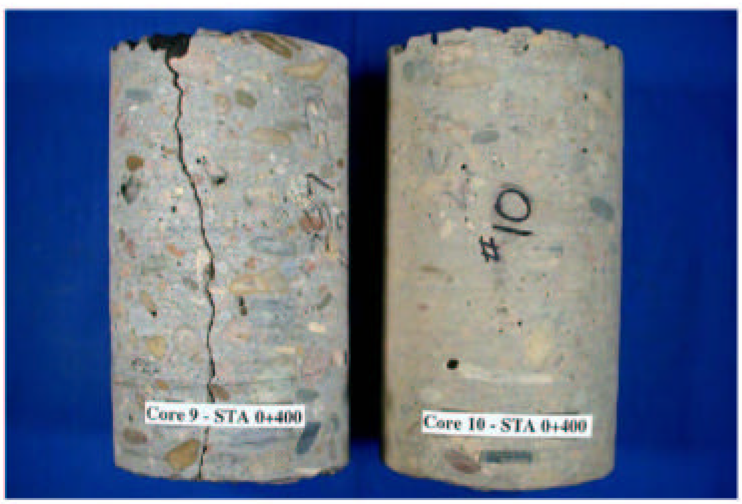


2b. Side view.

Fig. 2 (a & b) Concrete Cores 4 and 6, as received for analysis. Core 4 is from the cracked potion of the pavement and Core 6 is from the center of the lane.



3a. Top surface.



3b. Side view.

Fig. 3 (a & b) Concrete Cores 9 and 10, as received for analysis. Core 9 is from the cracked potion of the pavement and Core 10 is from the center of the lane.

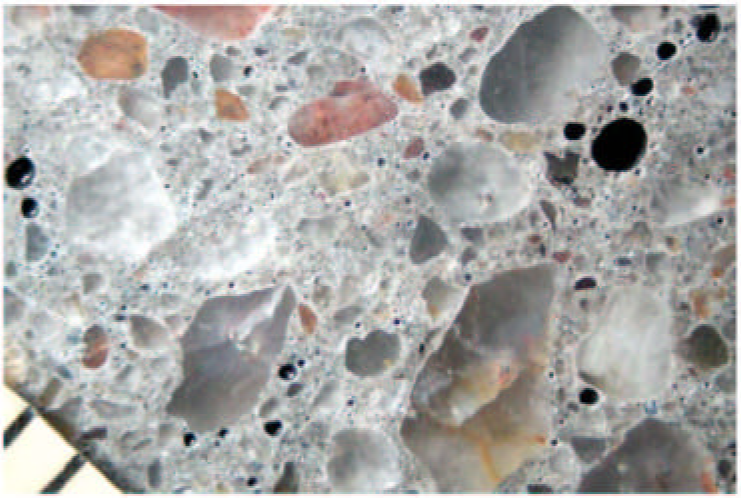


Fig. 4 Photomicrograph showing the air-void system in Core 1. Millimeter scale.

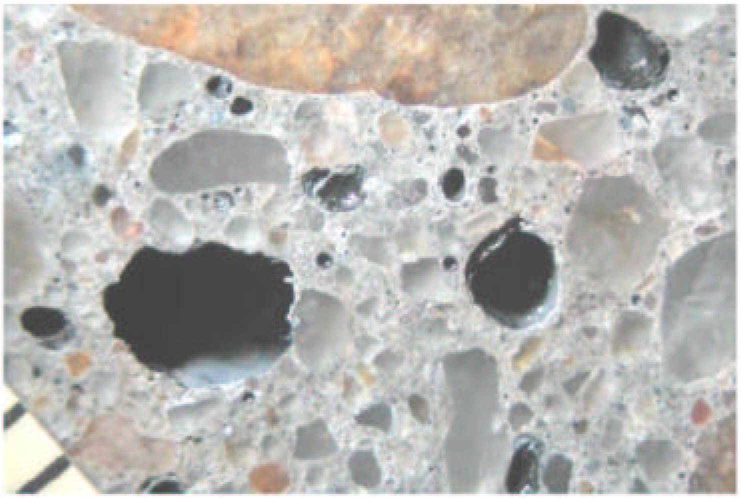


Fig. 5 Photomicrograph showing the air-void system in Core 3. Millimeter scale.

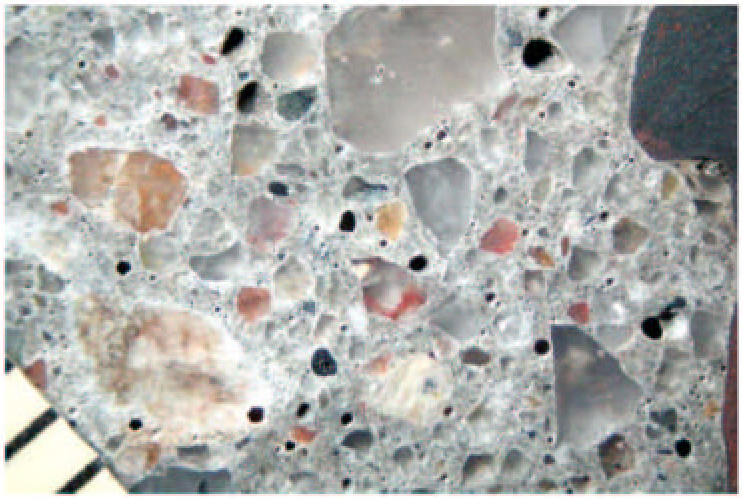


Fig. 6 Photomicrograph showing the air-void system in Core 4. Millimeter scale.

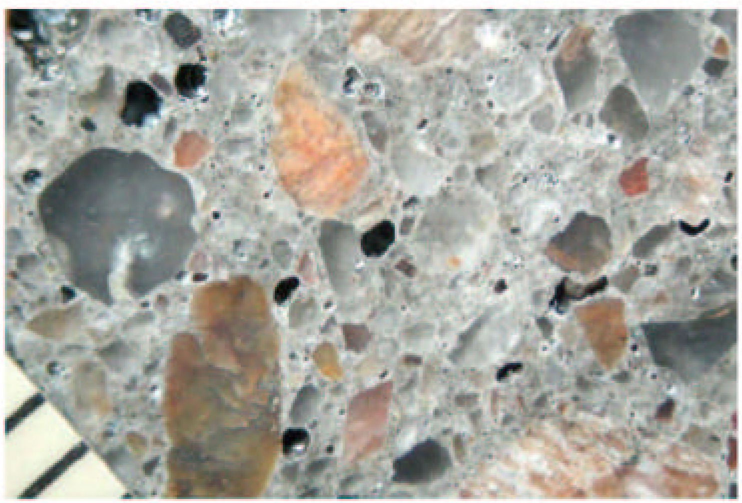


Fig. 7 Photomicrograph showing the air-void system in Core 6. Millimeter scale.

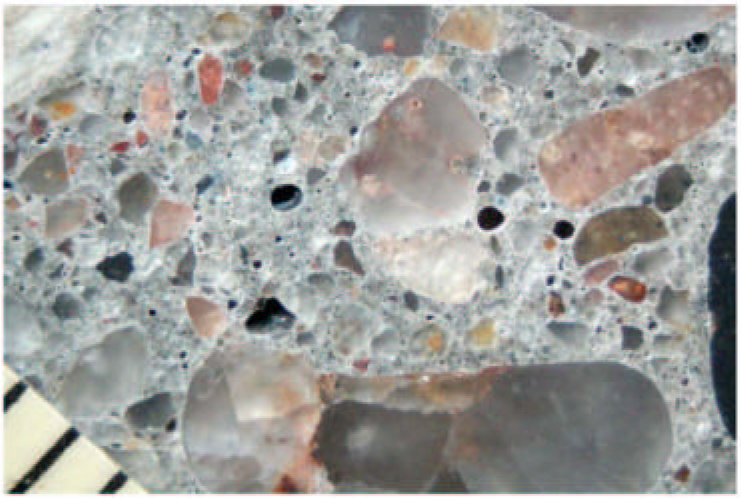


Fig. 8 Photomicrograph showing the air-void system in Core 9. Millimeter scale.

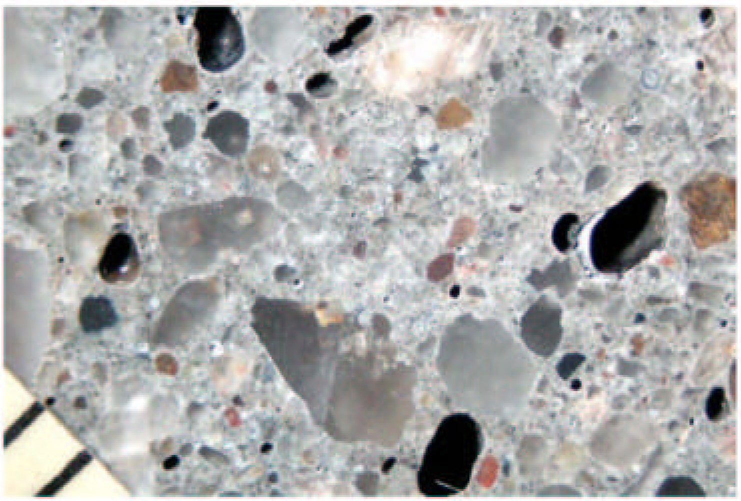


Fig. 9 Photomicrograph showing the air-void system in Core 10. Millimeter scale.

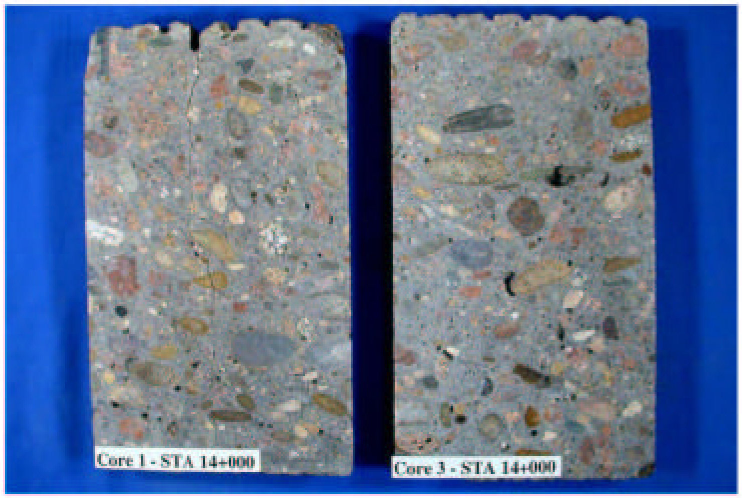


Fig. 10 Cut cross section of Cores 1 and 3 showing the longitudinal crack in Core 1.

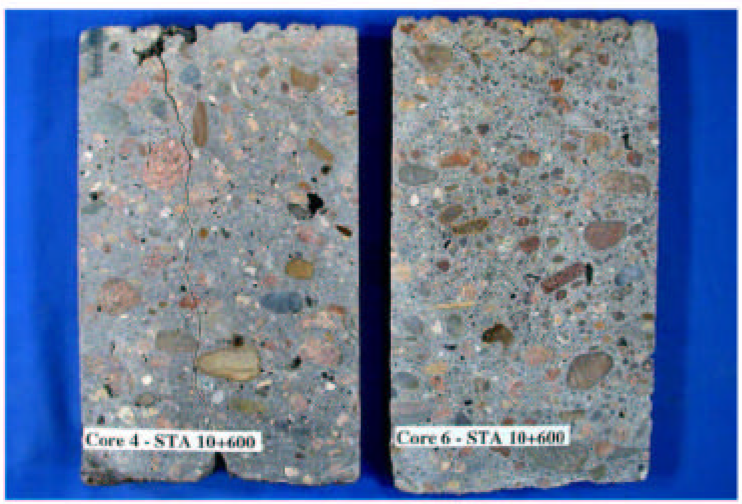


Fig. 11 Cut cross section of Cores 4 and 6 showing the longitudinal crack in Core 4.

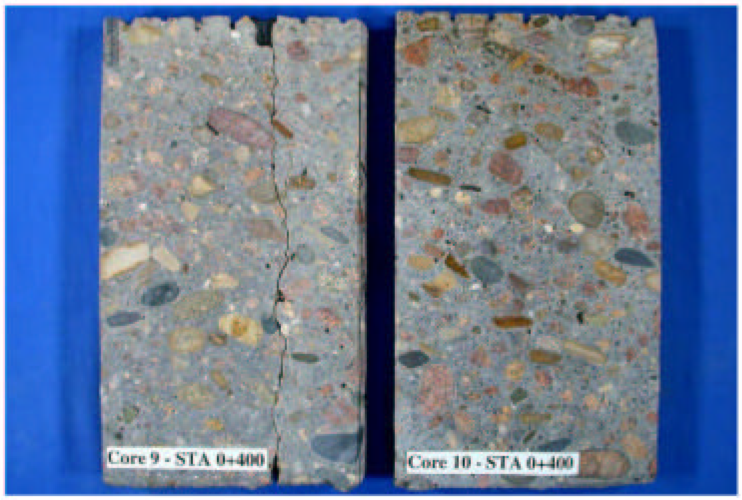


Fig. 12 Cut cross section of Cores 9 and 10 showing the longitudinal crack in Core 9.

REPORT OF AIR-VOID SYSTEM ANALYSIS

ASTM C 457-98 Modified-Point Count Method

CTL Project No.: 151817 Date: April 19, 2002

Client: Colorado DOT, Research Branch Tested By: Sang Y. Lee

Client Project: Pavement Concrete from US 287, Colorado

Maximum Size Aggregate: 1 in.

Sample No.	Total Air Content %	No. Voids/ inch	Specific Surface ($in.^2/in.^3$)	Spacing Factor (inch)	Number of Points	Length of Traverse (inches)
Core 1	2.3	6.6	1133	0.006	1426	95
Core 3	5.7	7.5	526	0.008	1426	95

Comments: The concrete specimens are air entrained, based on the presence of small, spherical voids in the hardened paste matrix and the measured air-void parameters.

American Concrete Institute,
ACI 201.2R-92
"Guide to Durable Concrete"
TABLE 1.4.3 RECOMMENDED AIR CONTENTS FOR FROST-RESISTANT CONCRETE

Nominal maximum Aggregate size in.	(mm)	Average air content, percent* Severe exposure +	Moderate exposure ++
3/8	(9.5)	7-1/2	6
1/2	(12.5)	7	5-1/2
3/4	(19)	6	5
1-1/2	(38)	5-1/2	4-1/2
3§	(75)	4-1/2	3-1/2
6§	(150)	4	3

* A reasonable tolerance for air content in field construction is ± 1-1/2 percent.

\+ Outdoor exposure in a cold climate where the concrete may be in almost continuous contact with moisture prior to freezing, or where deicing salts are used. Examples are pavements, bridge decks, sidewalks, and water tanks.

++ Outdoor exposure in a cold climate where the concrete will be only occasionally exposed to moisture prior to freezing, and where no deicing salts will be used. Examples are certain exterior walls, beams, girders, and slabs not in direct contact with soil.

§ These air contents apply to the whole mix, as for the preceding aggregate sizes. When testing these concretes, however, aggregate larger than 1-1/2 in. (38 mm) is removed by hand-picking or sieving and the air content is determined on the minus 1-1/2 in. (38 mm) fraction of the mix. (The field tolerance applies to this value.) From this the air content of the whole mix is computed.

There is conflicting opinion on whether air contents lower than those given in the table should be permitted for high-strength (more than 5500 psi) (37.8 MPa) concrete. This committee believes that where supporting experience and/or experimental data exists for particular combinations of materials, construction practices, and exposure, the air contents may be reduced by approximately 1 percent. [For maximum aggregate sizes over 1-1/2 in. (38 mm), this reduction applies to the minus 1-1/2 in. (38 mm) fraction of the mix.]

AIR-VOID SYSTEM: Most authorities consider the following air-void characteristics as representative of a system with adequate freeze-thaw resistance:

1. Calculated spacing factor (average maximum distance from any point in cement paste to edge of nearest air void)--less than 0.008 in. (0.20 mm).

2. Specific surface (surface area of the air voids)-- 600 $in.^2$ per cubic inch (23.6 mm^2/mm^3) of air-void volume, or greater.

3. Number of voids per linear inch (25 mm) of traverse be significantly greater than the numerical value of the percentage of air in the concrete.

References: (1) Design and Control of Concrete Mixtures, 13th Edition, Portland Cement Association, 1994, p. 60.
(2) American Concrete Institute, ACI 212.3R-7-98, (Section 2.2).

REPORT OF AIR-VOID SYSTEM ANALYSIS

ASTM C 457-98 Modified-Point Count Method

CTL Project No.: 151817 Date: April 19, 2002

Client: Colorado DOT, Research Branch Tested By: Sang Y. Lee

Client Project: Pavement Concrete from US 287, Colorado

Maximum Size Aggregate: 3/4 to 1 in.

Sample No.	Total Air Content %	No. Voids/ inch	Specific Surface ($in.^2/in.^3$)	Spacing Factor (inch)	Number of Points	Length of Traverse (inches)
Core 4	3.2	7.0	888	0.007	1426	95
Core 6	4.7	9.3	784	0.006	1351	90

Comments: The concrete specimens are air entrained, based on the presence of small, spherical voids in the hardened paste matrix and the measured air-void parameters.

American Concrete Institute,
ACI 201.2R-92
"Guide to Durable Concrete"
TABLE 1.4.3 RECOMMENDED AIR CONTENTS FOR FROST-RESISTANT CONCRETE

Nominal maximum Aggregate size in.	(mm)	Average air content, percent* Severe exposure +	Moderate exposure ++
3/8	(9.5)	7-1/2	6
1/2	(12.5)	7	5-1/2
3/4	(19)	6	5
1-1/2	(38)	5-1/2	4-1/2
3§	(75)	4-1/2	3-1/2
6§	(150)	4	3

* A reasonable tolerance for air content in field construction is ± 1-1/2 percent.

+ Outdoor exposure in a cold climate where the concrete may be in almost continuous contact with moisture prior to freezing, or where deicing salts are used. Examples are pavements, bridge decks, sidewalks, and water tanks.

++ Outdoor exposure in a cold climate where the concrete will be only occasionally exposed to moisture prior to freezing, and where no deicing salts will be used. Examples are certain exterior walls, beams, girders, and slabs not in direct contact with soil.

§ These air contents apply to the whole mix, as for the preceding aggregate sizes. When testing these concretes, however, aggregate larger than 1-1/2 in. (38 mm) is removed by hand-picking or sieving and the air content is determined on the minus 1-1/2 in. (38 mm) fraction of the mix. (The field tolerance applies to this value.) From this the air content of the whole mix is computed.

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3. Number of voids per linear inch (25 mm) of traverse be significantly greater than the numerical value of the percentage of air in the concrete.

References: (1) Design and Control of Concrete Mixtures, 13th Edition, Portland Cement Association, 1994, p. 60.
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REPORT OF AIR-VOID SYSTEM ANALYSIS

ASTM C 457-98 Modified-Point Count Method

CTL Project No.: 151817 Date: April 19, 2002

Client: Colorado DOT, Research Branch Tested By: Sang Y. Lee

Client Project: Pavement Concrete from US 287, Colorado

Maximum Size Aggregate: 3/4 in.

Sample No.	Total Air Content %	No. Voids/ inch	Specific Surface (in.^{2}/in.^{3})	Spacing Factor (inch)	Number of Points	Length of Traverse (inches)
Core 9	3.6	6.8	768	0.007	1351	90
Core 10	3.8	7.2	764	0.007	1351	90

Comments: The concrete specimens are air entrained, based on the presence of small, spherical voids in the hardened paste matrix and the measured air-void parameters.

American Concrete Institute,
ACI 201.2R-92
"Guide to Durable Concrete"
TABLE 1.4.3 RECOMMENDED AIR CONTENTS FOR FROST-RESISTANT CONCRETE

Nominal maximum Aggregate size in.	(mm)	Average air content, percent* Severe exposure +	Moderate exposure ++
3/8	(9.5)	7-1/2	6
1/2	(12.5)	7	5-1/2
3/4	(19)	6	5
1-1/2	(38)	5-1/2	4-1/2
3§	(75)	4-1/2	3-1/2
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