Impact of Curling, Warping, and Other Early-Age Behavior on Concrete Pavement Smoothness: Early, Frequent, and Detailed (EFD) Study

National Concrete Pavement Technology Center

Phase I Final Report
December 2005

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
FHWA DTFH61-01-X-00042 (Project 16)			
4. Title and Subtitle Impact of Curling, Warping, and Other Early-Age Behavior on Concrete Pavement Smoothness: Early, Frequent, and Detailed (EFD) Study		**5. Report Date** December 2005 **6. Performing Organization Code**	
7. Author(s) Halil Ceylan, Dennis J. Turner, Robert Otto Rasmussen, George K. Chang, James Grove, Sunghwan Kim, Chintakunta Satish Reddy		**8. Performing Organization Report No.**	
9. Performing Organization Name and Address Center for Transportation Research and Education Iowa State University 2901 South Loop Drive, Suite 3100 Ames, IA 50010-8634		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**	
12. Sponsoring Organization Name and Address Federal Highway Administration U.S. Department of Transportation 400 7th Street SW, HIPT-20 Washington, DC 20590		**13. Type of Report and Period Covered** Phase I Final Report **14. Sponsoring Agency Code**	
15. Supplementary Notes Visit www.ctre.iastate.edu for color PDF files of this and other research reports.			

16. Abstract

This report summarizes the activities in Phase I of "Assessing the Impact to Concrete Pavement Smoothness from Curling, Warping, and other Early-Age Behavior: Early, Frequent, and Detailed (Project 16)." The purpose of this project is to obtain detailed information about factors affecting pavement smoothness during the critical time immediately following construction by conducting a controlled field evaluation of three concrete pavement construction projects. In Phase I, both field and laboratory testing of the materials and construction process were conducted. Extensive pavement profiling was also performed during strategic times after placement.

As a whole, the data collection effort undertaken by the project team was a success. The result of this project is a large amount of quality data on the early-age effects of curling and warping on pavement smoothness. By using the data from this research and by using the mathematical models being developed as part of current FHWA studies and elsewhere, a better understanding will be gained of the complex relationship between concrete pavement smoothness and concrete pavement curling, warping, and other early-age behavior.

17. Key Words		**18. Distribution Statement**	
curling and warping—early-age behavior—smoothness		No restrictions.	
19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	103	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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December 2005

Principal Investigator
Halil Ceylan
Assistant Professor
Department of Civil, Construction and Environmental Engineering, Iowa State University

Co-Principal Investigators
Dennis J. Turner, Robert Otto Rasmussen, George K. Chang
The Transtec Group Inc.

James Grove
Associate Scientist
Center for Transportation Research and Education, Iowa State University

Graduate Assistants
Sunghwan Kim, Chintakunta Satish Reddy

Authors
Halil Ceylan, Dennis J. Turner, Robert Otto Rasmussen, George K. Chang, James Grove
Sunghwan Kim, Chintakunta Satish Reddy

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A report from
Center for Transportation Research and Education
Iowa State University
2901 South Loop Drive, Suite 3100
Ames, IA 50010-8634
Phone: 515-294-8103
Fax: 515-294-0467
www.ctre.iastate.edu

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ACKNOWLEDGMENTS

The principal investigator would like to thank the members of the Transtec Group Inc. for their involvement with this project, specifically Dennis J. Turner, M.S.E.; Robert Otto Rasmussen, Ph.D., P.E.; and George K. Chang, Ph.D., P.E. The crew of the Mobile Concrete Research Lab was also very helpful in the data collection and lab testing stages of this research.

INTRODUCTION

This report summarizes the activities in Phase I of "Assessing the Impact to Concrete Pavement Smoothness from Curling, Warping and other Early-Age Behavior: Early, Frequent, and Detailed (Project 16)." The purpose of this project is to obtain detailed information about factors affecting pavement smoothness during the critical time immediately following construction by conducting a controlled field evaluation of three concrete pavement construction projects. The results of this research will assist ongoing efforts within the FHWA. During the Phase I evaluation, both field and laboratory testing of the materials and construction process were conducted. Extensive pavement profiling was also performed during strategic times after placement. By using the data from this research and by using the mathematical models being developed as part of current FHWA studies and elsewhere, a better understanding will be gained of the complex relationship between concrete pavement smoothness and concrete pavement curling, warping, and other early-age behavior. While this project measured specific types of data, it was not conducted in a vacuum. The "Early, Frequent, and Detailed" (EFD) concept is a part of the strategic plan advanced in the FHWA's Task 15, now termed the CP Road Map.

This project has been organized into the four following tasks:

- Task 1: Program planning
- Task 2: Pre-visit data collection and briefing
- Task 3: Pavement instrumentation/monitoring and pavement testing
- Task 4: Post-visit documentation and data submission

During Phase I of this project, all tasks were fulfilled for the initial construction project on US 151 near Platteville, Wisconsin. Task 1 was fulfilled prior to the US 151 investigation, and resulted in the development of an overall testing plan. Tasks 2 and 3 were performed during the construction of US 151 near Platteville, Wisconsin from October 22 to 27, 2004. Although the data from the initial construction project has been reported and submitted, this report fulfills the remaining requirements of Task 4 for Phase I.

DATA COLLECTION

The data collected for this project includes design information, laboratory and materials tests, and in situ instrumentation and monitoring.

Pavement Design

The field evaluation was conducted during the construction of a 9.5-in. (240-mm) jointed plain concrete pavement (JPCP). The pavement was constructed over a 6-in. (152-mm) open-graded granular base. The concrete haul trucks backed down the grade to access the slipform paver. The transverse joint spacing was approximately 15 ft (4.6 m). The passing lane was approximately 12 ft (3.7 m) wide, and the travel lane was approximately 14 ft (4.3 m) wide, which includes a 2-ft (0.7-m) shoulder. An open-graded granular shoulder was added after construction.

Across the longitudinal joints, 24-in. (610-mm) tie-bars (size #4, 0.5 in. or 12.7 mm) were inserted approximately every 33 in. (838 mm). The slipform paver utilized an automated dowel bar inserter (DBI) that placed 18-in. (457-mm) long, 1.25-in. (32-mm) diameter smooth dowels approximately every 30 in. (762 mm) along the transverse joints.

Conventional saws were used to cut transverse and longitudinal joints to a depth of approximately 3 in. (76 mm) and to a width of approximately 0.5 in. (12.7 mm). As per Wisconsin Department of Transportation specifications, no joint cleaning or sealants were used. Appendix A contains photos of typical construction operations, including concrete delivery, paving, texturing, curing, sawing, and shouldering.

Pavement Materials

Obtaining fundamental properties of the paving materials was a key component of this project and aided in the correlation between construction projects, as well as in providing a foundation for future tests on the test sections. The concrete mixture design is provided in Table 1. The Blaine Fineness for the portland cement and fly ash was reported to be 3,774 and 5,337 cm^2/g, respectively. The strengths of the subbase and subgrade layers were not reported to the project team.

Table 1. Concrete mixture design

Component	Description	Batch weight
Portland cement	CEMEX - Type 1	395 lbs/yd^3
GGBFS		
Fly ash	ISG - Type C (spec. grav. = 2.40)	170 lbs/yd^3
Silica fume		
Coarse aggregate 1	Hartnett Quarry - limestone (spec. grav. = 2.607)	1,826 lbs/yd^3
Coarse aggregate 2		
Fine aggregate 1	J&R Sand - natural (spec. grav. = 2.612)	1,220 lbs/yd^3
Fine aggregate 2		
Water		203 lbs/yd^3
Admixture 1	GRT Polychem VR - air entrainer	8.0 oz/yd^3
Admixture 2	GRT Polychem 400NC - water reducer	17.0 oz/yd^3
Water/cementitious materials ratio		**0.36**
Air content		**7.00%**

The overall testing plan also prescribed a series of laboratory tests on the concrete mixture, shown in Appendix A. The splitting tensile (ASTM C 496) and compressive (ASTM C 39) strengths, as well as corresponding maturity values, are reported in Tables 2 and 3. The elastic modulus was also measured at various ages and is reported in Table 4. The coefficient of thermal expansion (CTE) measured from field-fabricated samples tested at 56 days was reported to be 1.044E-5 ε/°C.

Table 2. Splitting tensile strength results

Age (hrs)	Maturity, TTF (˚C-hr)	Splitting tensile strength	
		psi	MPa
12.	301	188	1.30
24	626	323	2.23
48	1262	373	2.57
96	2472	408	2.81
168	4122	448	3.09

Table 3. Compressive strength results

Age (hrs)	Maturity, TTF (˚C-hr)	Compressive strength	
		psi	MPa
12.	301	1198	8.26
24	626	2253	15.53
48	1262	2824	19.47
96	2472	3408	23.50
168	4122	4059	27.99

Using measured surface strains in three directions, the project team made estimates of the CTE, as shown in Table 5 and Figure 1. The ultrasonic pulse velocity (UPV) through the concrete was also measured at various ages and is reported in Figure 2. The data shows that the set time of the concrete occurred between 5 and 8 hours.

Table 4. Elasticity modulus test results

Age (hrs)	Elasticity Modulus	
	psi	MPa
12	1,806,977	12,459
24	2,567,664	17,703
48	2,759,456	19,026
96	3,273,770	22,572
168	3,160,825	21,793
672	4,601,131	31,724
1344	4,667,153	32,179

Table 5. Cumulative results for estimating CTE from surface strains

Direction	Estimated CTE (ε/°C)
Longitudinal	1.227E-05
Diagonal	1.175E-05
Transverse	1.654E-05
Average	1.352E-05

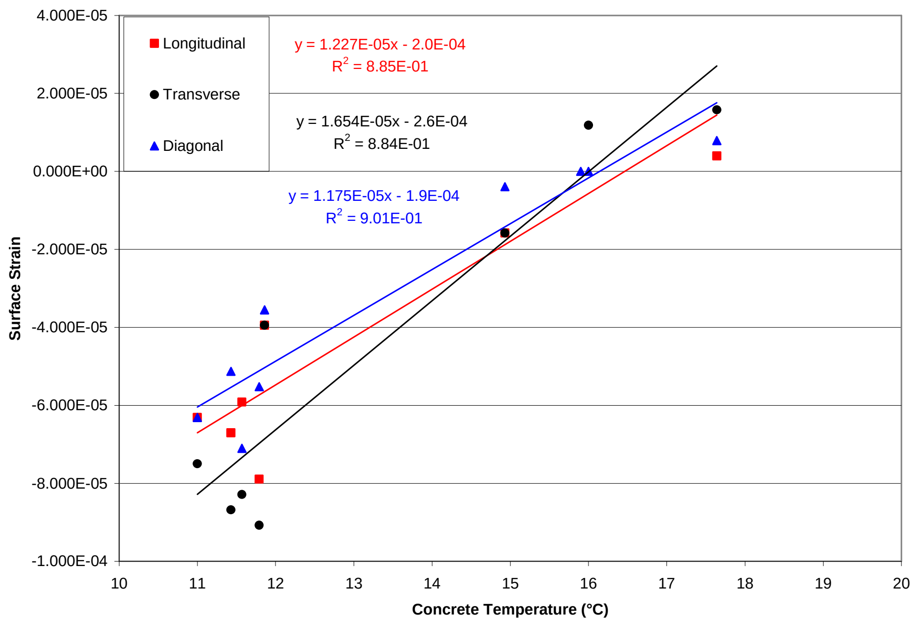

Figure 1. Estimation of CTE from surface strains

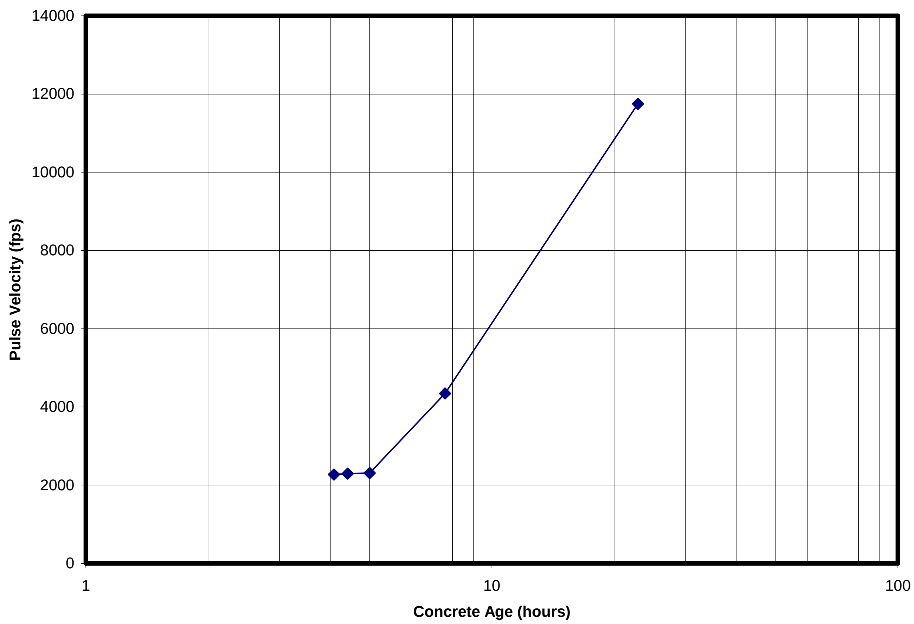

Figure 2. Ultrasonic pulse velocity results

Curling and Warping Monitoring

Two test sections, as shown in Figure 3, were selected to represent the entire pavement length. The selection criteria outlined in the overall testing plan included selecting a relatively flat grade and avoiding horizontal curves. Figure 4 diagrams the test sections and depicts the location of instrumentation within the 300-ft sections, including the corner Demec instrumentation at the free edge corners of slabs 10 and 11 (typical).

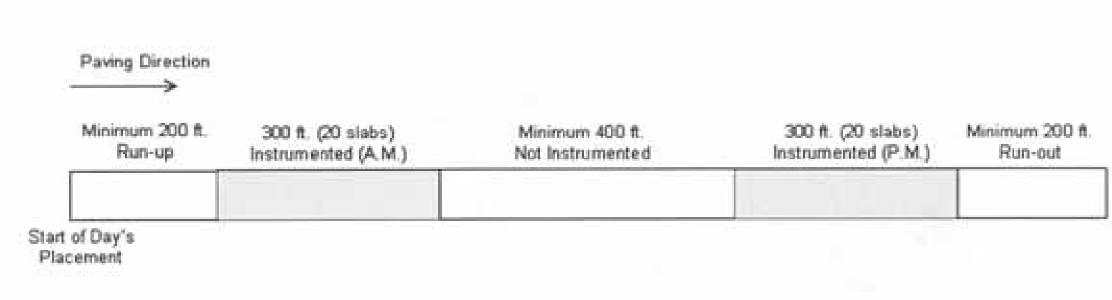

Figure 3. Test section layout

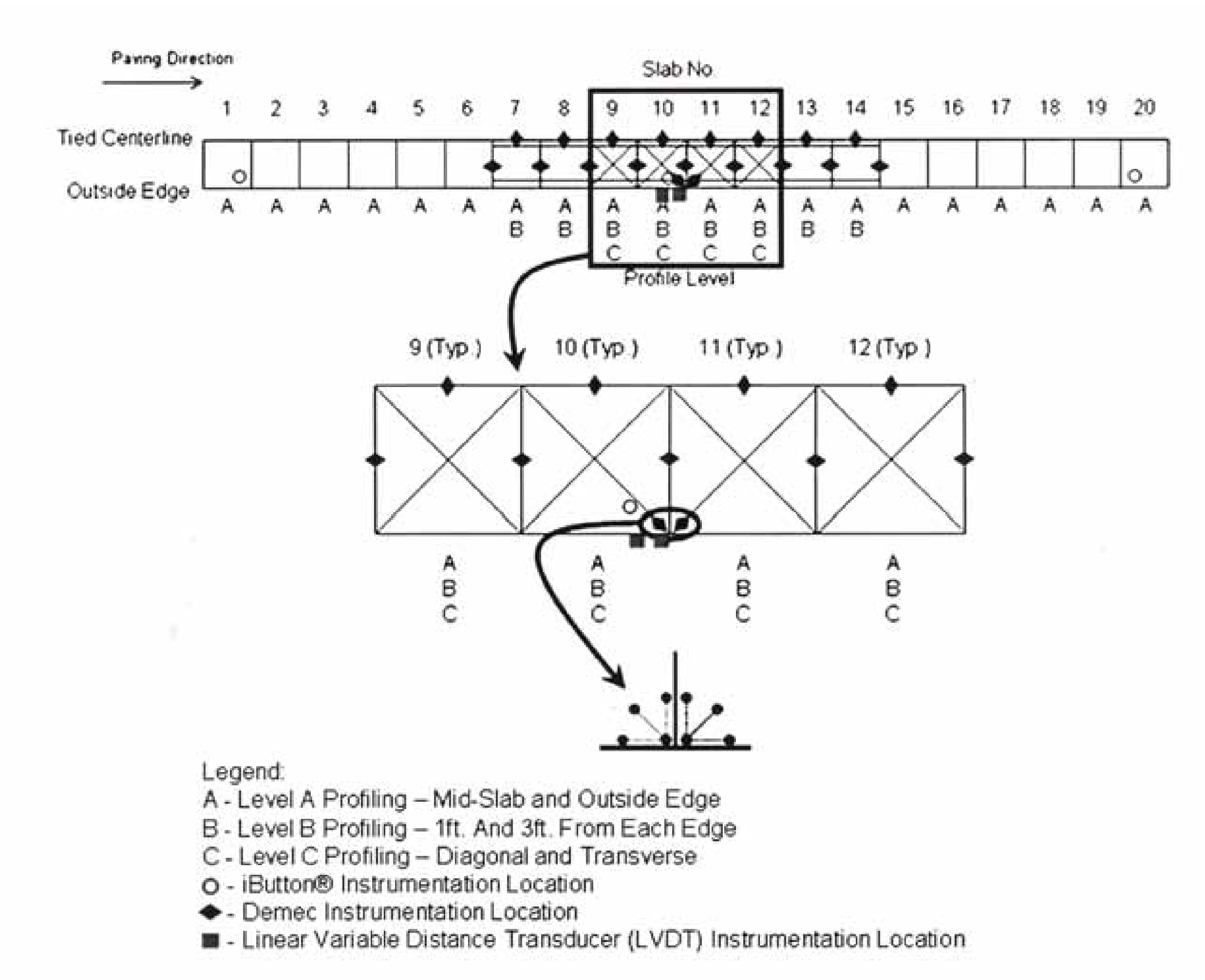

Figure 4. Instrumentation layout

Diurnal Testing

To capture changing slab curvature conditions due to varying slab temperature gradients, field monitoring activities were performed in a diurnal cycle. For example, it is known that upward slab curling, wherein the corners/edges of the slab curl up, occurs when the bottom of the slab is warmer at the bottom than at the top. The maximum upward curling condition generally occurs during early morning hours, just before sunrise. In a similar manner, downward slab curling occurs when the top of the slab is warmer than the bottom. The maximum downward curling condition generally occurs around noon or in the very early afternoon, when the surface of the slab is heated by the sun. These maximum conditions are highly dependent on climatic conditions, such as cloud cover, but in general these are the timeframes for the maximum slab temperature gradient. The project team documented the diurnal cycles by continuously recording the environmental conditions before, during, and after construction, as shown in Figure 5.

While the degree of slab curvature ultimately depends on the curvature "built in" during construction, the majority of JPCP pavements exhibit diurnal changes in slab curvature. To accommodate for the additional effects of heat generated through cement hydration, two test sections were instrumented to correspond to morning and afternoon construction. This diurnal testing of multiple sections provides a better understanding of the changes in slab curl that occur on a daily basis.

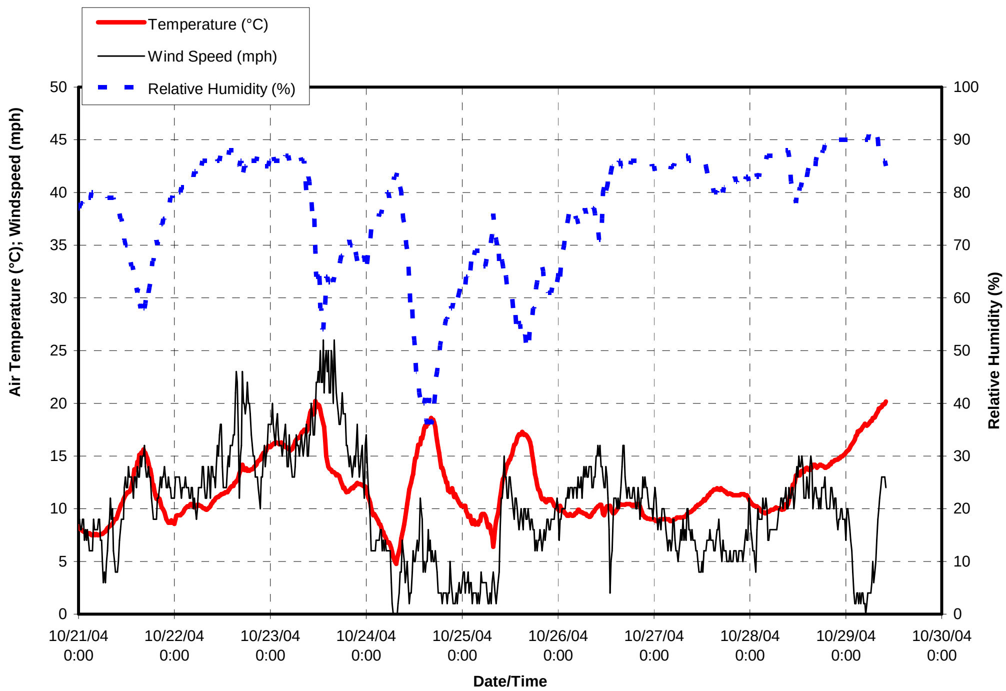

Figure 5. Recorded environmental conditions

Slab Temperature Gradient

Knowing the temperature gradient in the pavement slab when profile measurements are collected is essential for understanding the correlation between changes in curvature and changes in the temperature gradient. Slab temperature data was logged at five-minute intervals throughout the field evaluation period. Appendices B and C contain the temperature and maturity records for the two test sections.

Temperature instrumentation consisted of Thermochron iButtons® attached to a stake at different depths and placed before the paver approximately 3 ft (0.9 m) from the pavement edge, as shown in Figure 6. iButtons® are self-contained temperature sensors that measure and log temperature, along with date and time. This information is used to determine the temperature profile during diurnal tests, as well as maturity-estimated strengths. A typical instrumentation setup is shown in Figure 7. In addition to logging slab temperature profiles during the evaluation period, the project team reset the iButtons® to log at a 3-hour interval for seasonal monitoring, allowing up to 256 days before downloading is necessary. Instrumentation leadwires were extended beyond the shoulder in a pipe and buried to facilitate future access, as shown in Figure 8.

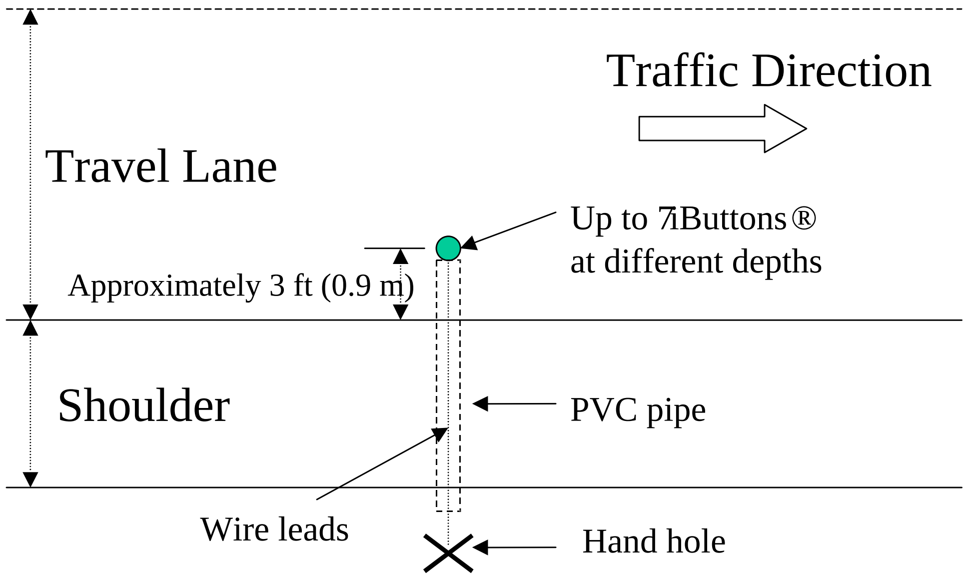

Figure 6. Temperature Instrumentation Layout

Figure 7. Temperature instrumentation

Figure 8. Temperature instrumentation leadwire protection for future access

Relative and Absolute Joint Opening

To aide in the characterization of slab curling and warping, it was necessary to characterize the movement of transverse and longitudinal joints immediately following construction, as well as during diurnal cycles. Beginning shortly after construction, the project team attached stainless steel discs to the pavement surface to be used with DEMEC caliper measurements. Figures 9 and 10 show the discs on the concrete surface for joint movement and surface strain measurements, respectively.

Figure 9. DEMEC points in the "peacock" pattern

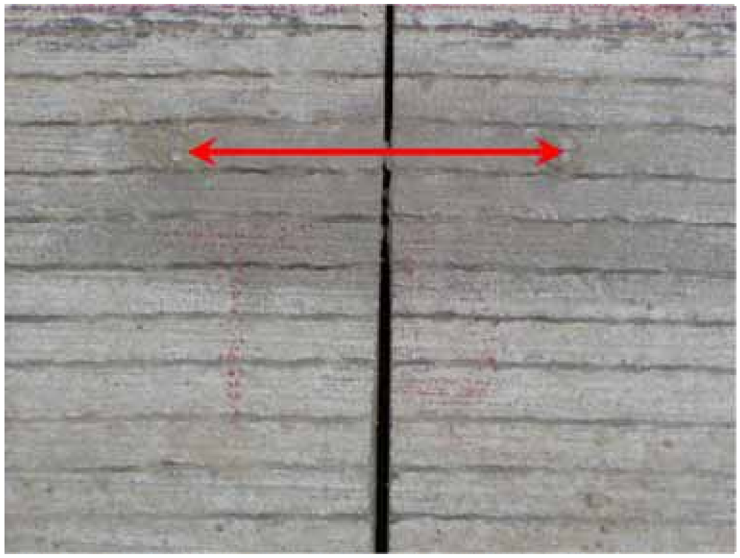

Figure 10. DEMEC points across a transverse joint

These points were installed at the prescribed locations for each instrumentation location listed below:

- nine successive transverse joints, to measure joint movement
- eight successive longitudinal joint locations, to measure joint movement
- two "peacock" patterns at slab corners, to measure surface strain (CTE)

Since this instrumentation involved a new concrete pavement with joints that had not fully begun to open and close in direct response to temperature changes, the project team referenced all relative joint movements to the initial reading taken at each location. To further aide in the analysis, the date, time, concrete age, and average concrete temperature was provided with each recording. Figure 1 and Table 5 provide the cumulative results for surface strains observed in the "peacock" pattern. It should be noted that this construction took place late in the paving season and resulted in a relatively small range of concrete temperatures. Cumulative results for relative joint movements are provided in Appendices B and C for the morning and afternoon paving test sections, respectively.

Vertical Slab Movement

The project team installed linear variable distance transducers (LVDTs) at strategic locations in one slab within each test section. In addition to installations at the corner and mid-slab free edge, as shown in Figure 11, an additional six LVDTs were installed in the same slab to provide data for additional modeling. These measurements were used by the project team as a reference to the absolute slab movement due to curling and warping. LVDT installations on the slab edge and interior slab areas are depicted in Figure 12. The LVDTs were connected to dataloggers, which logged data at a 10-minute interval. The data records for both test sections are provided in Appendices B and C for the morning and afternoon paving test sections, respectively.

Figure 11. LVDT installation (Transtec)

Figure 12. LVDT installation (Iowa State University)

Inclinometer Profiling

The central feature in this research program is the extensive early-age smoothness measurements. The project team rented a FACE Company Dipstick® profiler to measure pavement surface profiles in three patterns during diurnal cycles, as shown in Figure 13. Level A profiles followed a loop along the outside pavement edge and at mid-slab for all 20 slabs. Level B profiles followed a loop at 1.5 ft and 3 ft from the outside free edge and 1 ft and 3 ft from the longitudinal joint for 4 successive slabs near the center of the 20-slab test section. Level C profiles followed a "butterfly" loop of transverse and diagonal traces for the same slabs tested in Level B. Due to the time required to measure all profile patterns during a single diurnal cycle, the testing plan was modified by only collecting Level B profiles in the mid-afternoon diurnal period and by reducing the number of slabs in the Level B profile pattern.

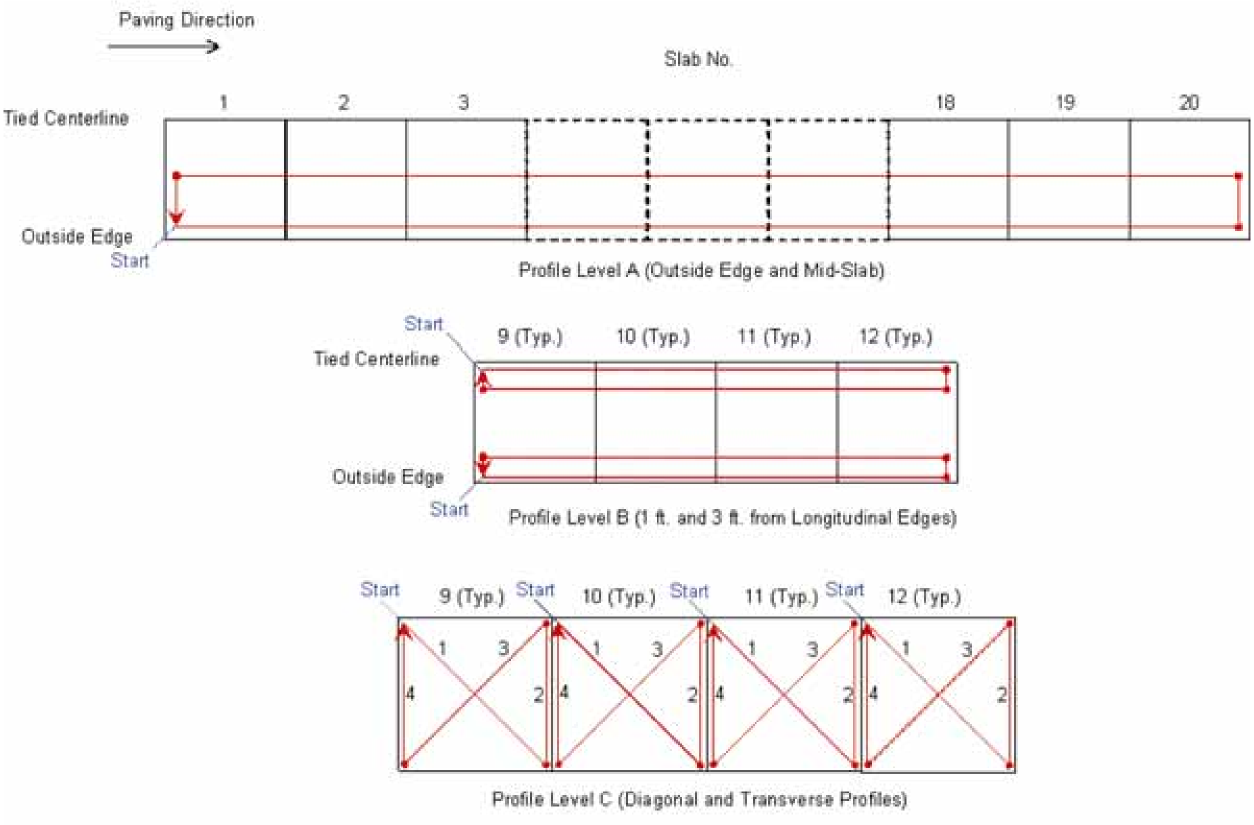

Figure 13. Inclinometer profiling levels and paths

The profile information on the longitudinal paths (Levels A and B) was processed using the FHWA Pavement Profile Viewing and Analysis (ProVAL). Since the inclinometer profiler records raw elevation data, the profiles were passed through a Butterworth bandpass filter to remove trends from grade changes for visual evaluation. Ride statistics, namely the International Roughness Index (IRI), Pre-Transformed Ride Number (PTRN), and Ride Number, do not require detrending and were calculated directly from the raw profiles. The calculated ride statistics, as well as other measured parameters, such as pavement temperature, are summarized in the following tables:

- Tables 6 and 7: Level A, Morning Paving Test Section
- Tables 8, 9, 10, and 11: Level B, Morning Paving Test Section
- Table 12 and 13: Level A, Afternoon Paving Test Section
- Tables 14, 15, 16, and 17: Level B, Afternoon Paving Test

Plots of filtered profiles from Levels A and B are also provided in Appendices B and C for the morning and afternoon paving test sections, respectively.

The "butterfly" pattern of Level C was profiled to measure individual slab curl in diurnal cycles. Due to skewed joint sawcuts, which created non-square slab corners, each of the four profile segments were measured independently. Each segment was first filtered to remove the effect of grade changes and then normalized to the initial profile for comparison purposes. As opposed to this profile pattern on existing JPCP slabs, the joints have not begun to fully form and move with the diurnal cycle, which complicates the analysis. The DEMEC measurements of relative joint opening are necessary to explain the Level C profile results. The results from each path on the four slabs of each test section are reported in Appendices B and C.

Table 6. Morning paving, Level A, slab edge profile summary

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
1A121E	10/21/2004 7:00	21.25	19.5	8.0	93	151.4	3.41
1A122E	10/21/2004 10:30	24.75	18.9	10.2	96.1	172.7	3.23
1A31E	10/22/2004 6:00	44.25	15.4	10.4	94.8	175.6	3.21
1A33E	10/22/2004 13:00	51.25	14.8	11.6	92.9	172.8	3.23
1A41E	10/23/2004 7:30	69.75	15.6	16.9	100.6	145.3	3.46
1A43E	10/23/2004 13:00	75.25	17.3	18.4	98.4	149.8	3.43
1A51E	10/24/2004 9:00	95.25	11.6	7.6	97.2	150.4	3.42
1A53E	10/24/2004 14:00	100.25	15.1	16.7	98.6	150.6	3.42
1A61E	10/25/2004 6:30	116.75	11.6	8.2	96	143	3.48
1A63E	10/25/2004 13:10	123.42	13.9	16.1	96.5	146.9	3.45
1A71E	10/26/2004 8:30	142.75	11.8	9.5	93.3	148.2	3.44
1A81E	10/27/2004 6:45	165.00	10.9	9.2	94.5	144.4	3.47
1A83E	10/27/2004 13:00	171.25	11.6	10.9	94.4	147.1	3.45

Table 7. Morning paving, level A, mid-slab profile summary

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	RNPI (in./mi)	RN
1A122M	10/21/2004 10:30	24.75	18.9	10.2	70.7	120.9	3.68
1A41M	10/23/2004 7:30	69.75	15.6	16.9	83	127.3	3.63
1A43M	10/23/2004 13:00	75.25	17.3	18.4	73.8	114.3	3.75
1A51M	10/24/2004 9:00	95.25	11.6	7.6	76.5	116.9	3.72
1A53M	10/24/2004 14:00	100.25	15.1	16.7	78.1	114.7	3.74
1A61M	10/25/2004 6:30	116.75	11.6	8.2	73.3	117.7	3.71
1A63M	10/25/2004 13:10	123.42	13.9	16.1	73.3	106.4	3.82
1A71M	10/26/2004 8:30	142.75	11.8	9.5	72.4	108.3	3.8
1A81M	10/27/2004 6:45	165.00	10.9	9.2	78.7	111.4	3.77

Table 8. Morning paving, level B, profile summary (1.5 ft from free edge)

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
1B143	10/23/2004 14:00	76.25	17.9	15.0	62.2	134.2	3.56
1B153	10/24/2004 15:00	101.25	15.8	17.8	71.1	115.6	3.73
1B163	10/25/2004 14:10	124.42	14.9	17.0	64.2	121.6	3.68
1B173	10/26/2004 14:00	148.25	12.1	9.6	64.2	128.6	3.61
1B183	10/27/2004 14:00	172.25	11.8	11.4	68.3	138.2	3.53

Table 9. Morning paving, level B, profile summary (3 ft from free edge)

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
1B243	10/23/2004 14:00	76.25	17.9	15.0	94.2	151.1	3.41
1B253	10/24/2004 15:00	101.25	15.8	17.8	96.9	166.4	3.28
1B263	10/25/2004 14:10	124.42	14.9	17.0	88.2	143	3.48
1B273	10/26/2004 14:00	148.25	12.1	9.6	83.8	142.8	3.49
1B283	10/27/2004 14:00	172.25	11.8	11.4	84.1	136.3	3.54

Table 10. Morning paving, level B, profile summary (3 ft from longitudinal joint)

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
1B343A	10/23/2004 14:00	76.25	17.9	15.0	109.5	157.3	3.36
1B353A	10/24/2004 15:00	101.25	15.8	17.8	121	177.3	3.2
1B363A	10/25/2004 14:10	124.42	14.9	17.0	117.3	180.3	3.17
1B373A	10/26/2004 14:00	148.25	12.1	9.6	122.1	167.7	3.27
1B383A	10/27/2004 14:00	172.25	11.8	11.4	120.8	170.8	3.25

Table 11. Morning paving, level B, profile summary (1 ft from longitudinal joint)

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
1B343B	10/23/2004 14:00	76.25	17.9	15.0	87.8	113.5	3.75
1B353B	10/24/2004 15:00	101.25	15.8	17.8	89.2	127.9	3.62
1B363B	10/25/2004 14:10	124.42	14.9	17.0	89.8	123	3.66
1B373B	10/26/2004 14:00	148.25	12.1	9.6	96.7	135.3	3.55
1B383B	10/27/2004 14:00	172.25	11.8	11.4	91.3	125.4	3.64

Table 12. Afternoon paving, level A, slab edge profile summary

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
2A23E	10/21/2004 16:00	23.75	20.1	15.3	99.2	211.9	2.93
2A31E	10/22/2004 8:30	40.25	14.6	10.1	101.4	190.3	3.09
2A42E	10/23/2004 9:45	65.50	16.2	18.7	99.8	164.9	3.3
2A43E	10/23/2004 15:15	71.00	17.9	13.7	89.5	165.2	3.29
2A51E	10/24/2004 7:30	87.25	12.5	10.3	92.5	158.8	3.35
2A53E	10/24/2004 12:00	91.75	14.0	14.2	90.4	156.2	3.37
2A61E	10/25/2004 8:20	112.08	11.6	8.4	85.1	149.1	3.43
2A63E	10/25/2004 15:15	119.00	16.3	17.2	88.2	144.9	3.47
2A71E	10/26/2004 6:30	134.25	12.1	9.6	88.1	162.8	3.31
2A81E	10/27/2004 8:30	160.25	10.9	9.6	88.5	145.8	3.46
2A83E	10/27/2004 15:00	166.75	12.1	11.8	91.3	148.3	3.44

Table 13. Afternoon paving, level A, mid-slab profile summary

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
2A31M	10/22/2004 8:30	40.25	14.6	10.1	73.4	122.1	3.67
2A42M	10/23/2004 9:45	65.50	16.2	18.7	84.1	269.4	2.53
2A43M	10/23/2004 15:15	71.00	17.9	13.7	71.9	112.6	3.76
2A51M	10/24/2004 7:30	87.25	12.5	4.8	67.4	114.8	3.74
2A53M	10/24/2004 12:00	91.75	14.0	14.2	71.7	121.4	3.68
2A61M	10/25/2004 8:20	112.08	11.6	8.4	69.9	117.6	3.72
2A63M	10/25/2004 15:15	119.00	16.3	17.2	74.7	119.7	3.7
2A71M	10/26/2004 6:30	134.25	12.1	9.6	68.9	124.9	3.65
2A81M	10/27/2004 8:30	160.25	10.9	9.6	68.1	122.9	3.67
2A83M	10/27/2004 15:00	166.75	12.1	11.8	72.6	118.6	3.71

Table 14. Afternoon paving, level B, profile summary (1.5 ft from free edge)

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
2B143A	10/23/2004 16:15	72.00	17.7	13.3	61.2	159.8	3.34
2B153A	10/24/2004 13:00	92.75	15.0	16.1	60.3	135.1	3.55
2B163A	10/25/2004 16:15	120.00	16.9	16.9	60.1	121.9	3.68
2B183A	10/27/2004 16:00	167.75	12.1	11.8	55.6	127.3	3.63

Table 15. Afternoon paving, level B, profile summary (3 ft from free edge)

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
2B143B	10/23/2004 16:15	72.00	17.7	13.3	60.4	145.5	3.46
2B153B	10/24/2004 13:00	92.75	15.0	16.1	72.9	137.4	3.53
2B163B	10/25/2004 16:15	120.00	16.9	16.9	58.4	116.9	3.72
2B183B	10/27/2004 16:00	167.75	12.1	11.8	59.2	106.2	3.82

Table 16. Afternoon paving, level B, profile summary (3 ft from longitudinal joint)

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
2B243A	10/23/2004 16:15	72.00	17.7	13.3	47.7	118.1	3.71
2B253A	10/24/2004 13:00	92.75	15.0	16.1	48.8	105	3.84
2B263A	10/25/2004 16:15	120.00	16.9	16.9	47.4	109.5	3.79
2B283A	10/27/2004 16:00	167.75	12.1	11.8	44.2	107.2	3.81

Table 17. Afternoon paving, level B, profile summary (1 ft from longitudinal joint)

File name	Date/time	Age (hrs)	Avg. pavement temp. (°C)	Ambient temp. (°C)	IRI (in./mi)	PTRN (in./mi)	RN
2B243B	10/23/2004 16:15	72.00	17.7	13.3	70	148.7	3.43
2B253B	10/24/2004 13:00	92.75	15.0	16.1	67.4	138.1	3.53
2B263B	10/25/2004 16:15	120.00	16.9	16.9	56.8	109.3	3.79
2B283B	10/27/2004 16:00	167.75	12.1	11.8	54.7	84.8	4.04

SUMMARY AND RECOMMENDATIONS

As in any aggressive field instrumentation and monitoring plan, the project team faced several issues at the first construction site. It was immediately evident that the capabilities of he inclinometer profiler selected were inadequate for the schedule outlined in the overall testing plan. The short amount of time in the early morning diurnal cycle combined with the relatively slow speed of the profiler forced the project team to only collect a shortened Level B profile in the mid-afternoon diurnal period. However, this problem was alleviated in the remaining instrumentation projects (in Phase II) by renting a faster, more expensive profiler. The new profiler allowed the project team to collect all profiles in both the morning and afternoon diurnal cycles and to extend the Level B profile pattern to include all slabs within each test section.

In addition to the inadequacy of the profiler, the overall testing plan was too aggressive for temperature instrumentation. It was found that only small variations existed between the three instrumentation locations within each test section. For the Phase II construction projects, the project team therefore installed temperature instrumentation at a single location within each test section.

While at the first construction site, the project team was also unable to install Hygrochron humidity sensors in the concrete test section due to concern that installation would affect the concrete surface and possibly the edge slump on the fresh concrete. However, the project team successfully installed the instrumentation in the remaining construction projects in Phase II.

To facilitate additional modeling, the project team was asked to install all LVDTs in the Phase II construction projects in adjacent slabs. The field data collected from the LVDT instrumentation will be compared to the finite element modeling solutions in the next phase of the project. This change will help the researchers understand the early age behavior of concrete pavement systems in more detail.

As a whole, the data collection effort undertaken by the project team was a success. The result of this project is a large amount of quality data on the early-age effects of curling and warping on pavement smoothness.

CURRENT WORK

The lessons learned from the initial instrumentation effort were applied in the Phase II construction projects. The project team instrumented and monitored newly constructed pavement in Burlington, Iowa, in June 2005 and near Marshalltown, Iowa, in July 2005 to complete the field instrumentation component of the overall project. This information will be presented in the Phase II report.

APPENDIX A. PHOTO LOG

Figure A1. Base preparation and concrete delivery operations

Figure A2. Concrete delivery operations

Figure A3. Paver and dowel bar inserter operations

Figure A4. Dowel bar inserter operations

Figure A5. Paving operations

Figure A6. Straightedge operations

Figure A7. Texturing operations

Figure A8. Curing operations

Figure A9. Transverse sawcut operations

Figure A10. Transverse sawcut operations

Figure A11. Longitudinal sawcut operations

Figure A12. Inclinometer profiling

Figure A13. Inclinometer profiling

Figure A14. Temperature instrumentation installation

Figure A15. Temperature instrumentation installation

Figure A16. Temperature instrumentation installation

Figure A17. Temperature instrumentation installation

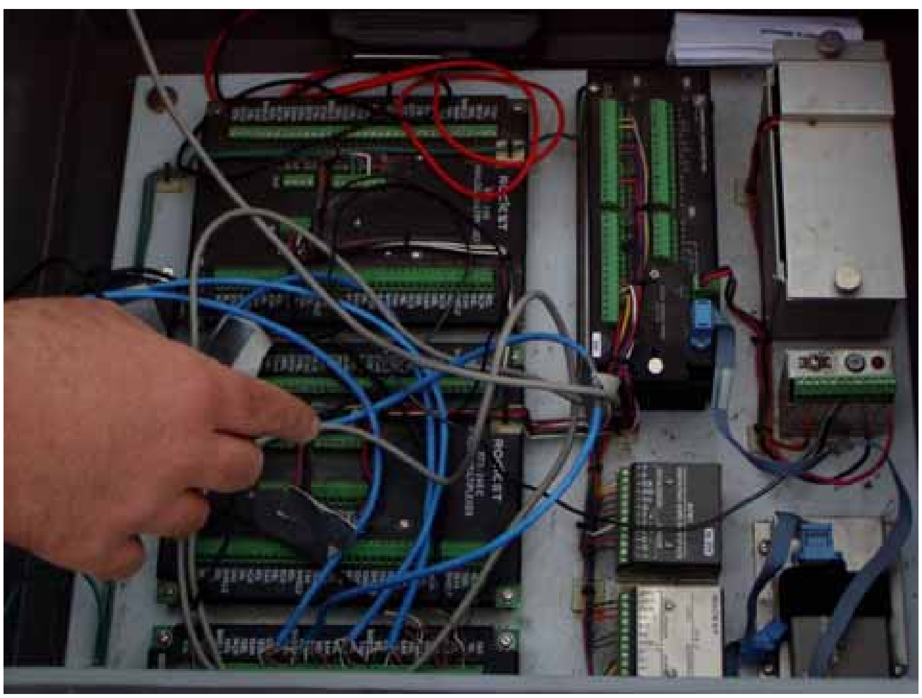

Figure A18. LVDT datalogger

Figure A19. LVDT installation (Iowa State University)

Figure A20. LVDT installation (Transtec)

Figure A21. Pavement coring

Figure A22. Corner DEMEC installation

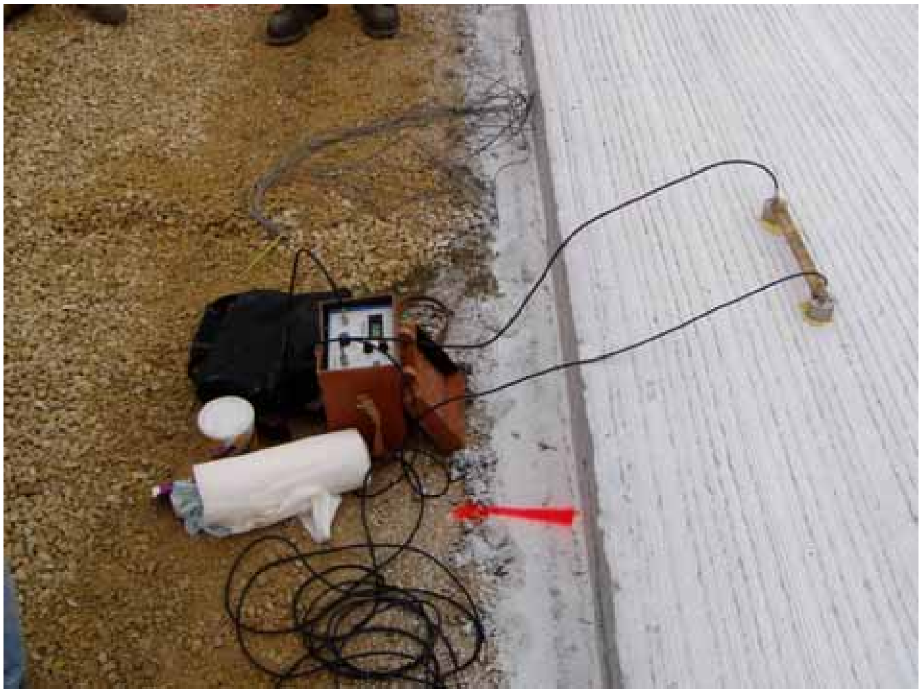

Figure A23. Ultrasonic pulse velocity

Figure A24. Iowa State University Mobile Concrete Research Lab

Figure A25. PCC elastic modulus test

Figure A26. PCC compressive strength test

Figure A27. PCC splitting tensile test

Figure A28. Coefficient of thermal expansion test

APPENDIX B. MORNING PAVING TEST SECTION

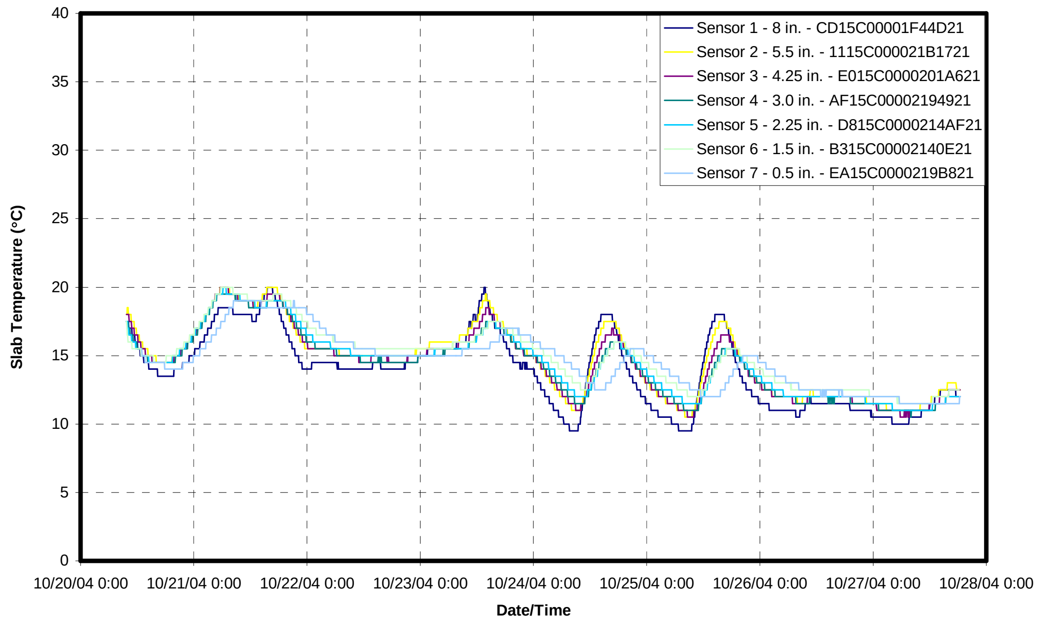

Figure B1. Slab temperature data

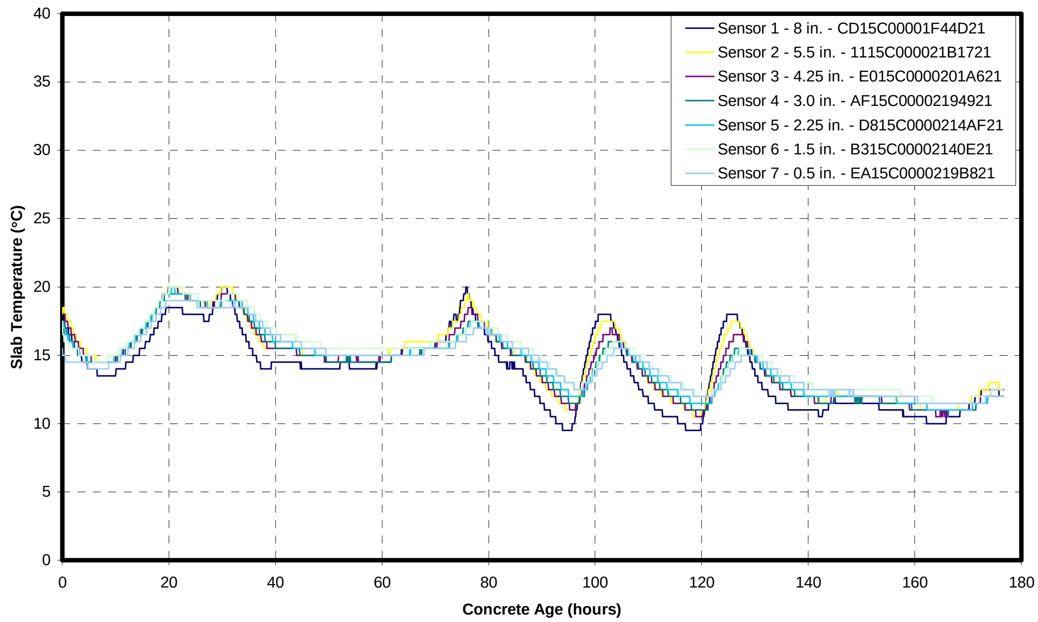

Figure B2. Slab temperature data

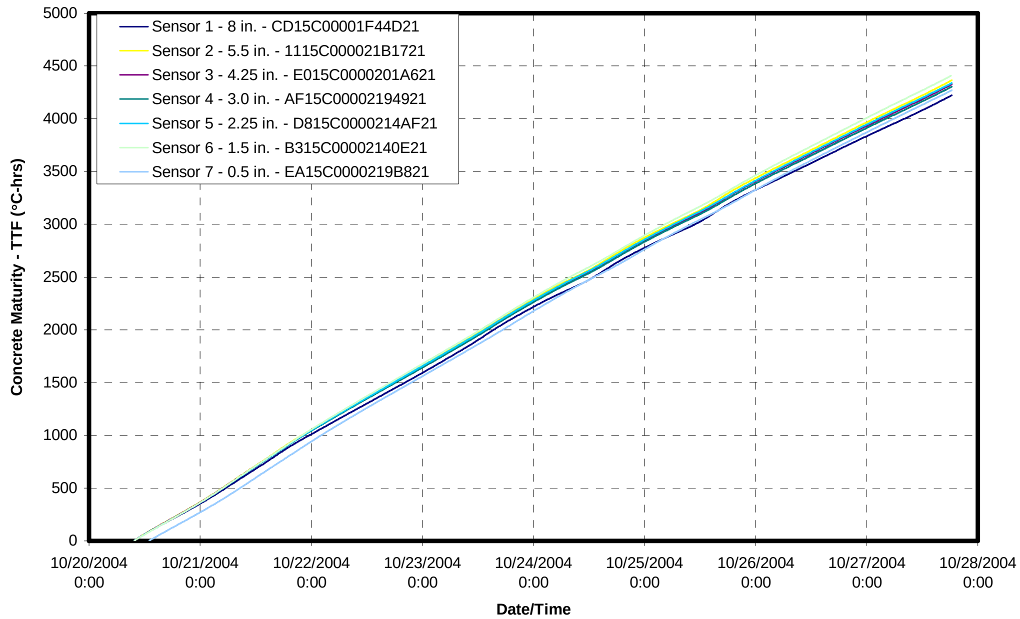

Figure B3. Slab maturity data

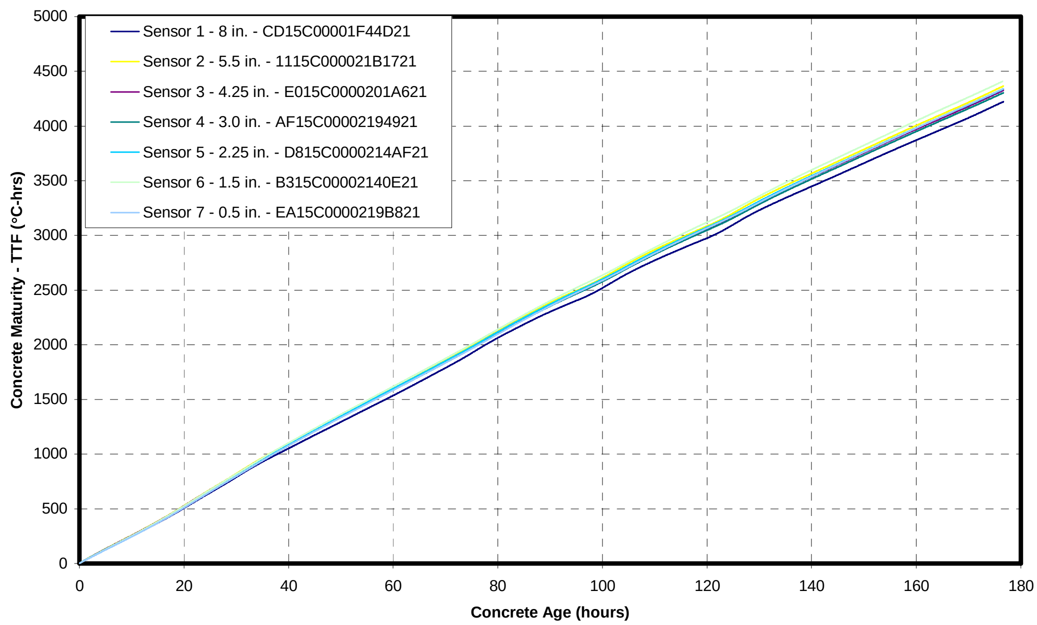

Figure B4. Slab maturity data

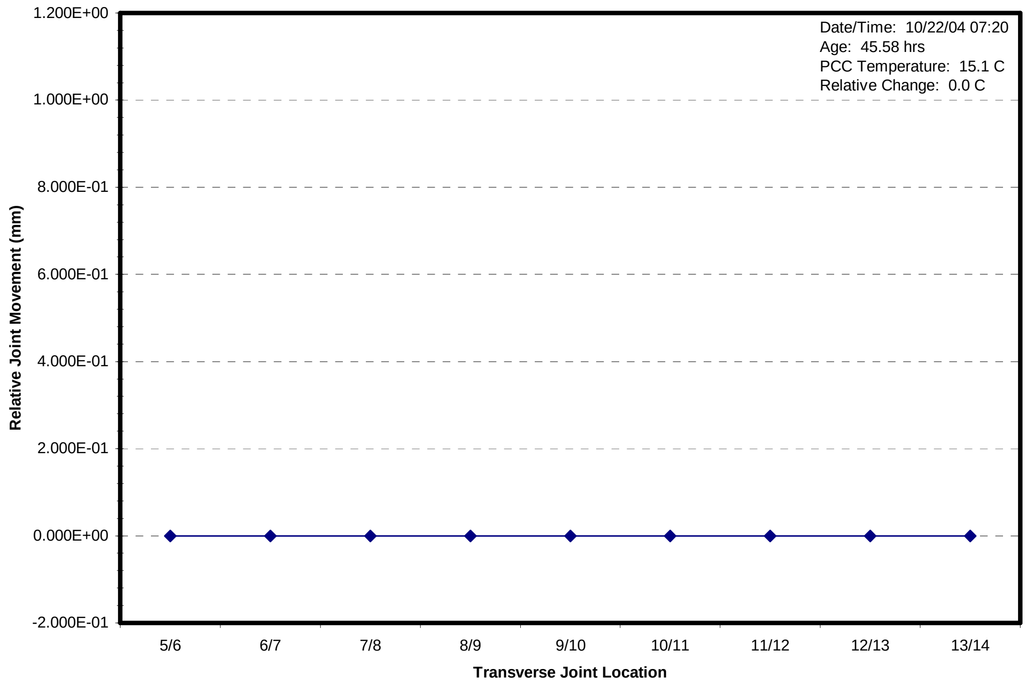

Figure B5. Transverse joint relative opening

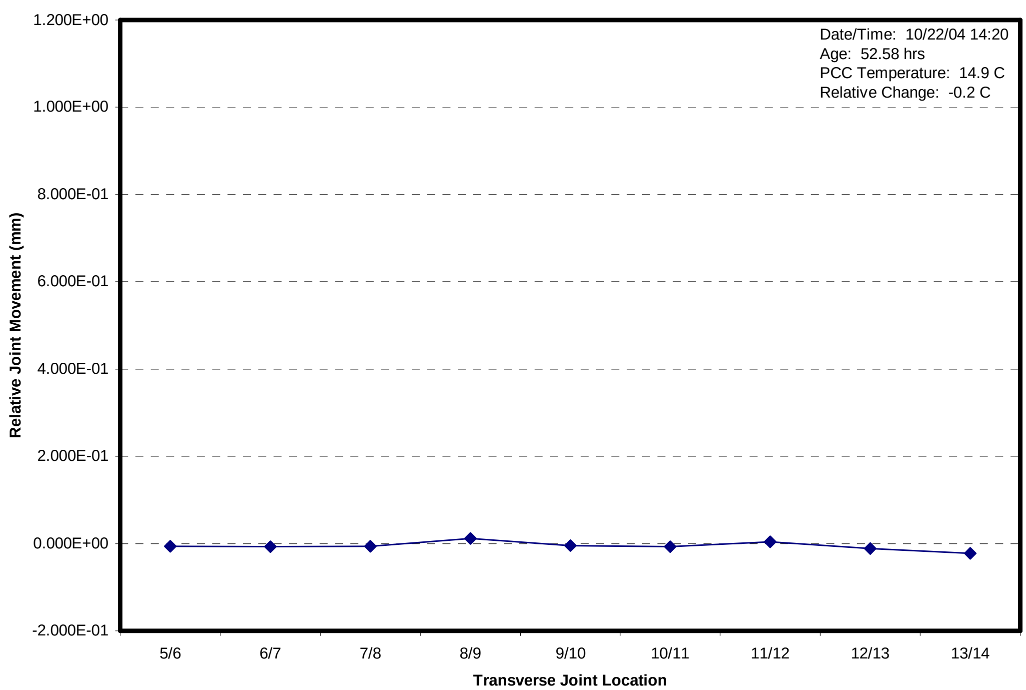

Figure B6. Transverse joint relative opening

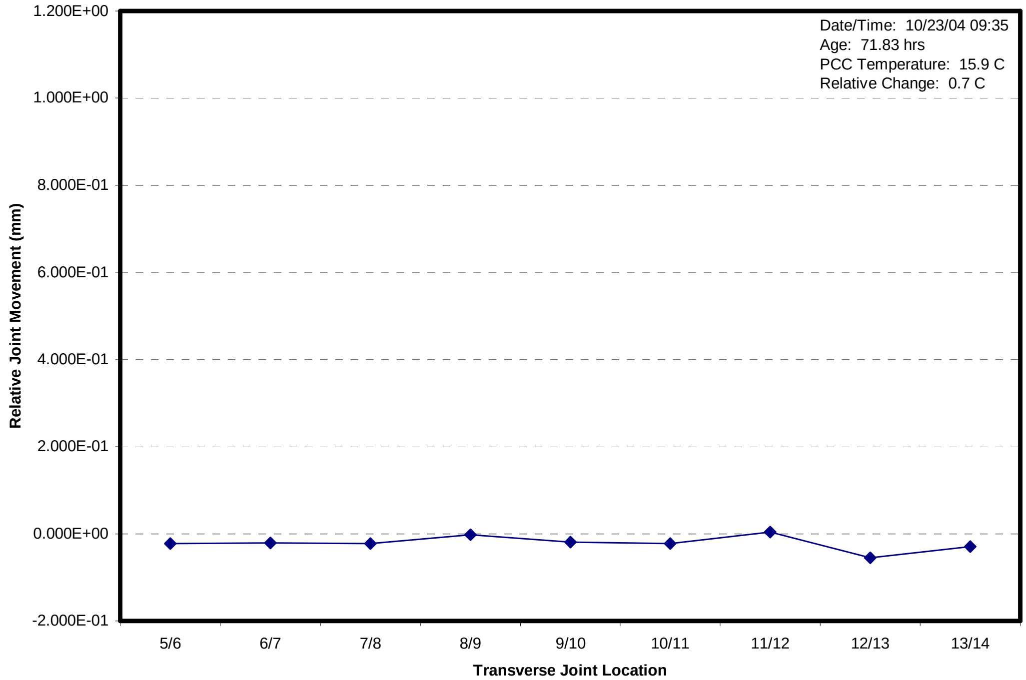

Figure B7. Transverse joint relative opening

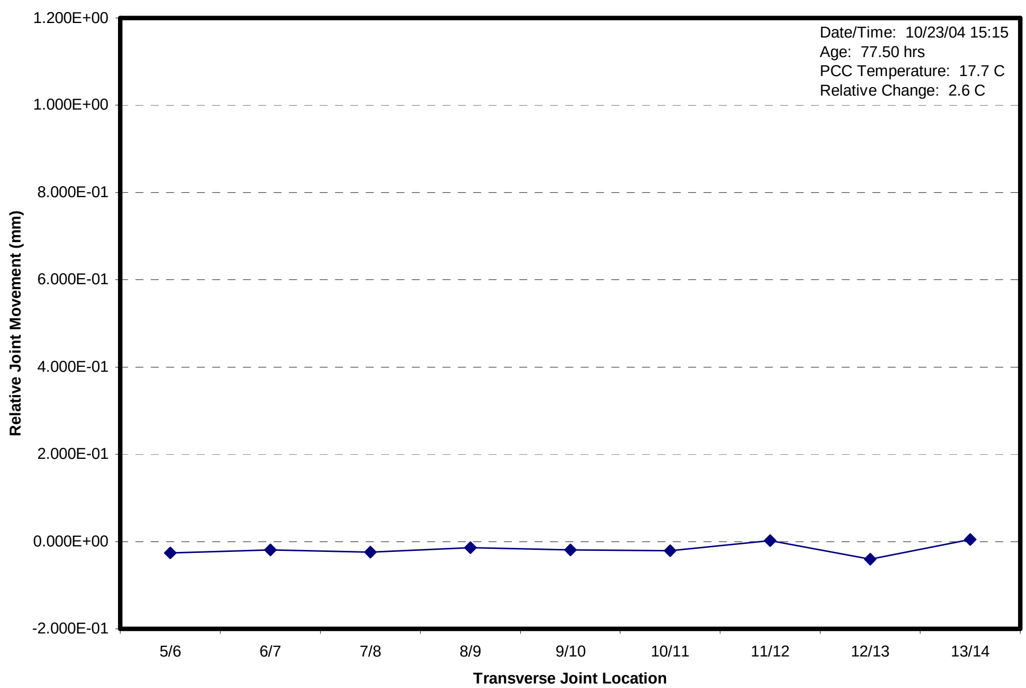

Figure B8. Transverse joint relative opening

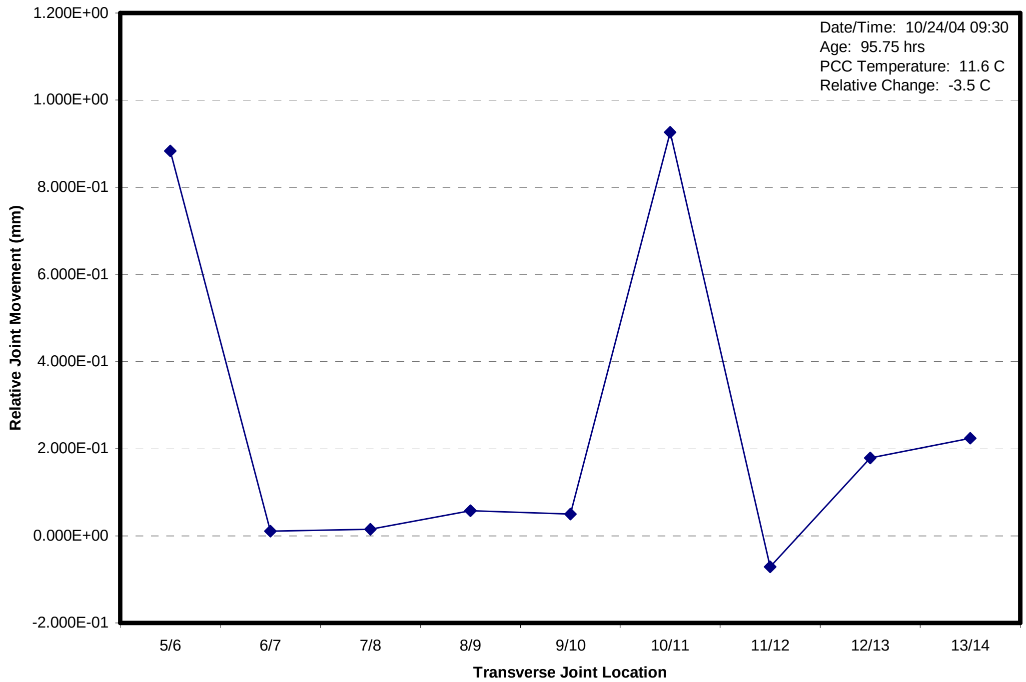

Figure B9. Transverse joint relative opening

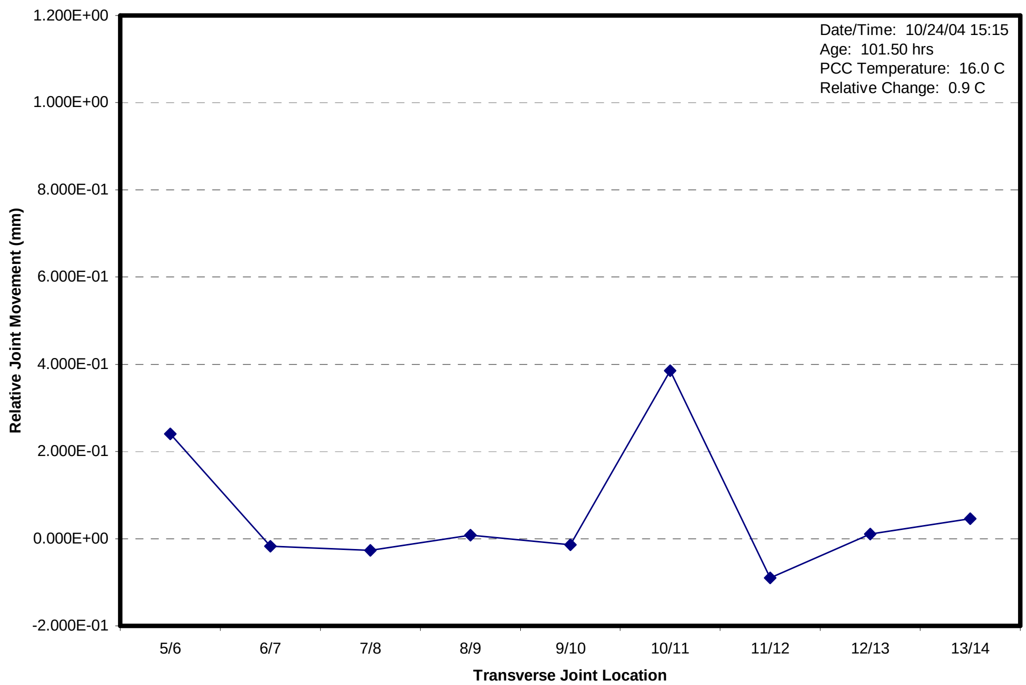

Figure B10. Transverse joint relative opening

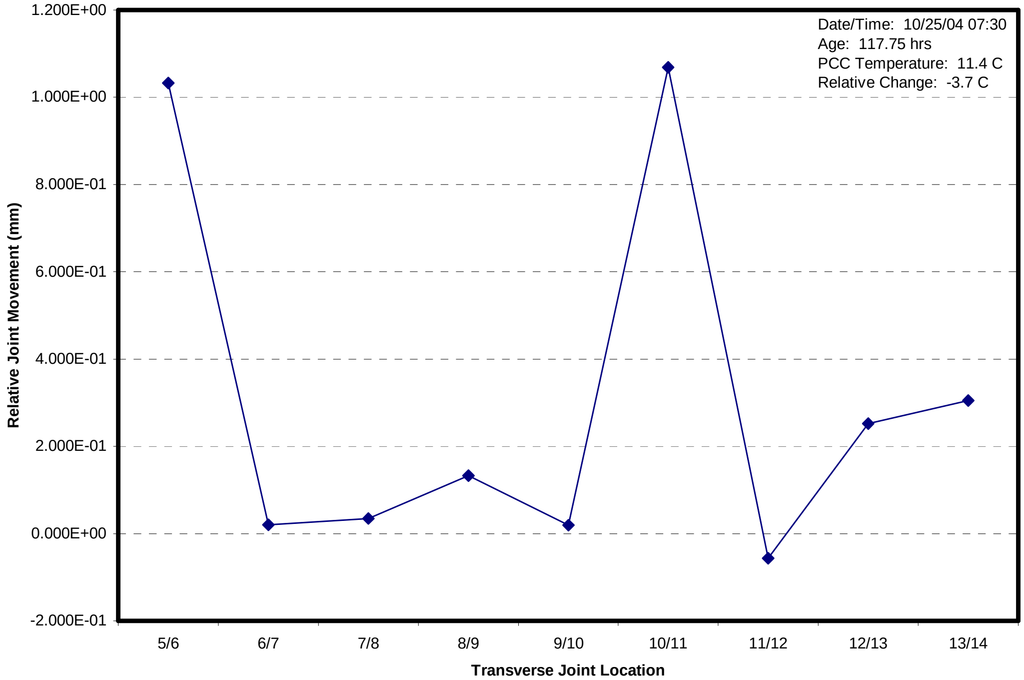

Figure B11. Transverse joint relative opening

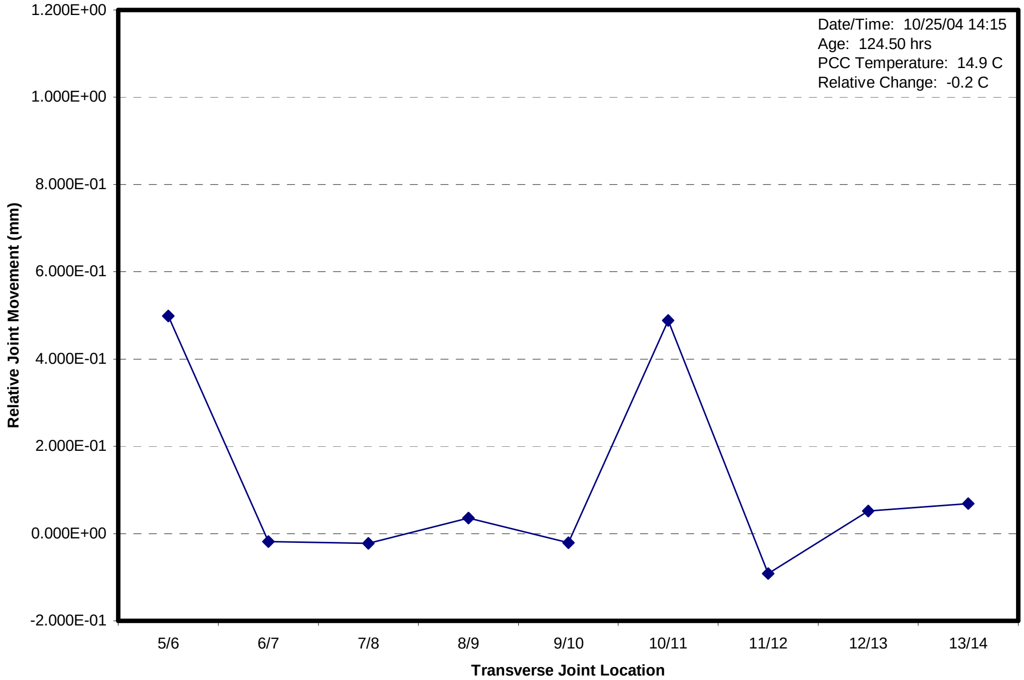

Figure B12. Transverse joint relative opening

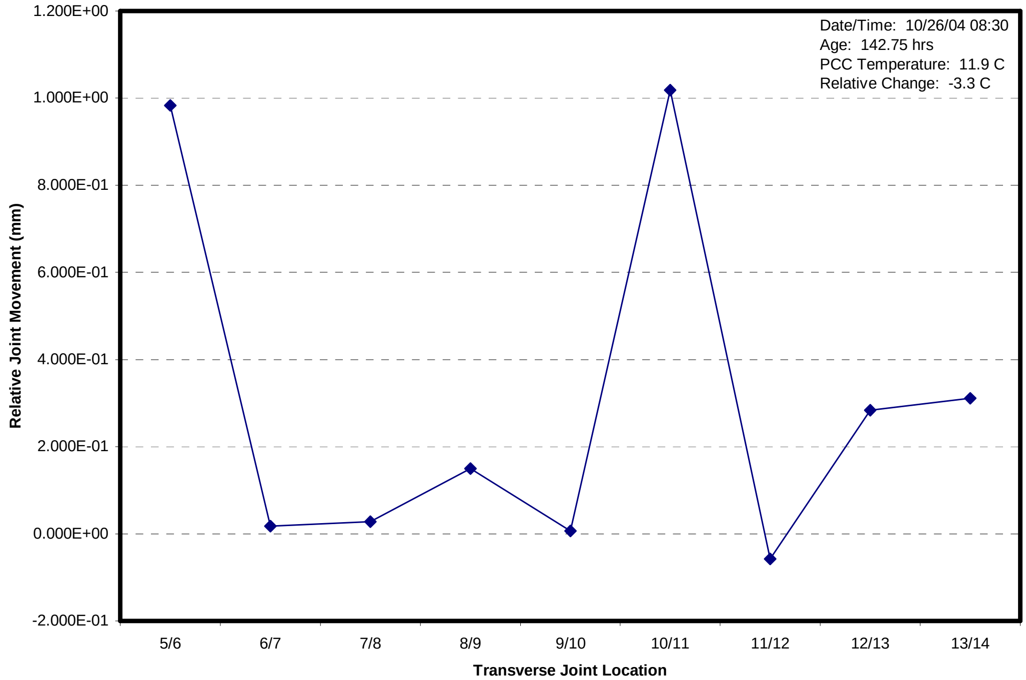

Figure B13. Transverse joint relative opening

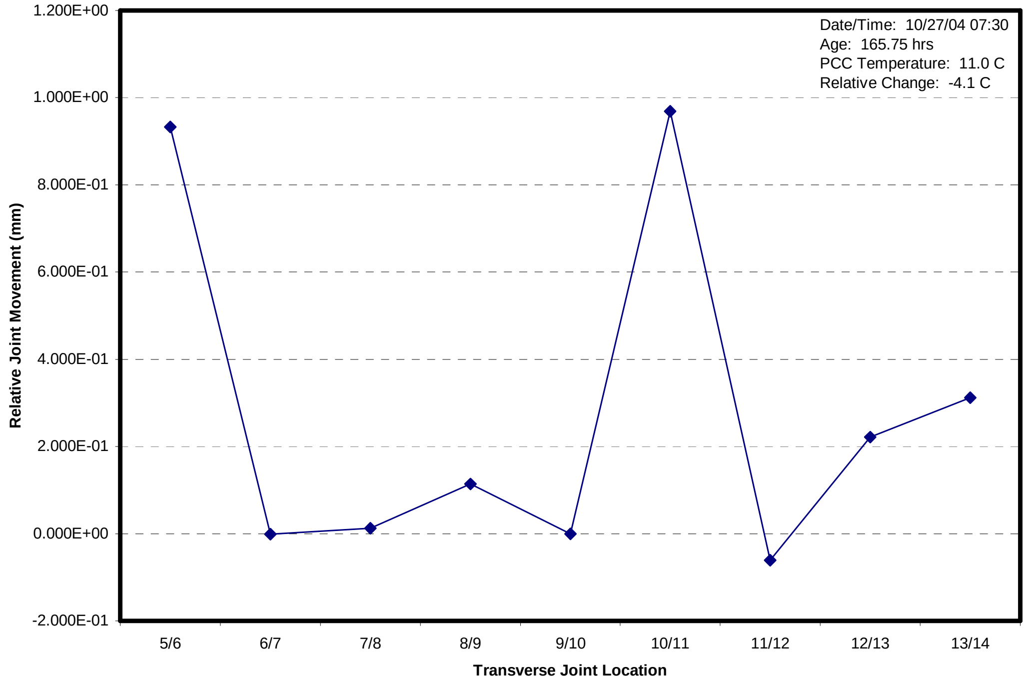

Figure B14. Transverse joint relative opening

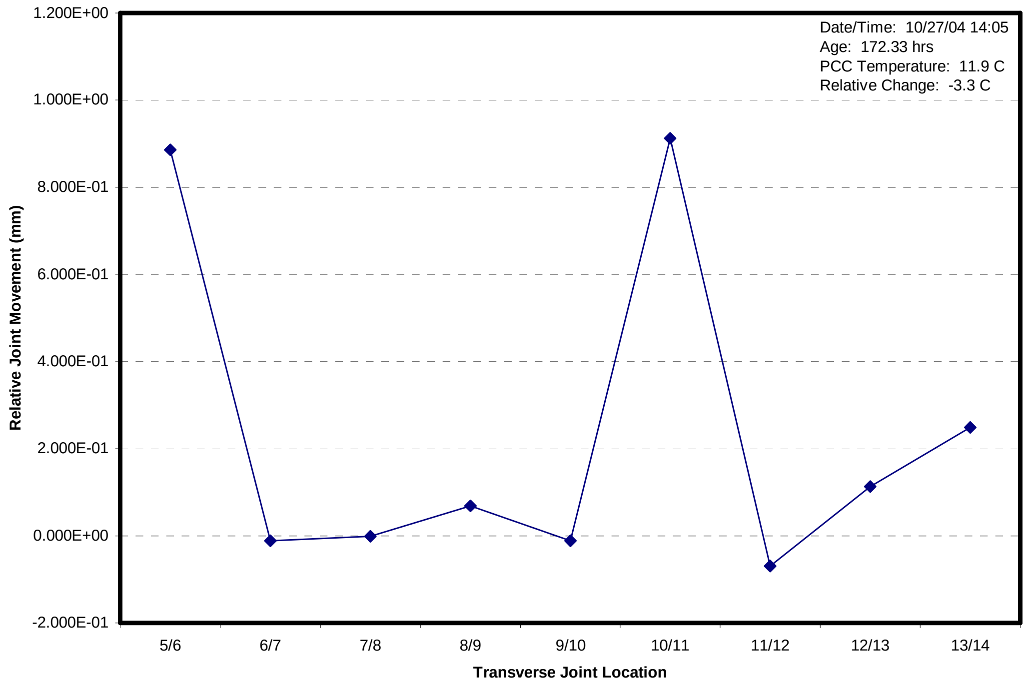

Figure B15. Transverse joint relative opening

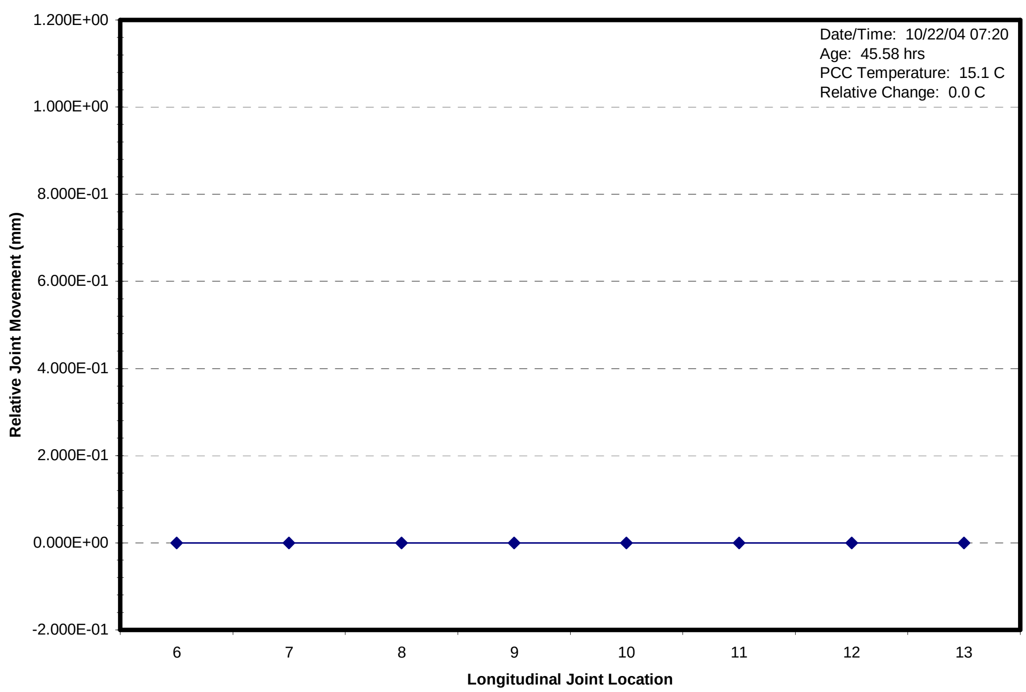

Figure B16. Longitudinal joint relative opening

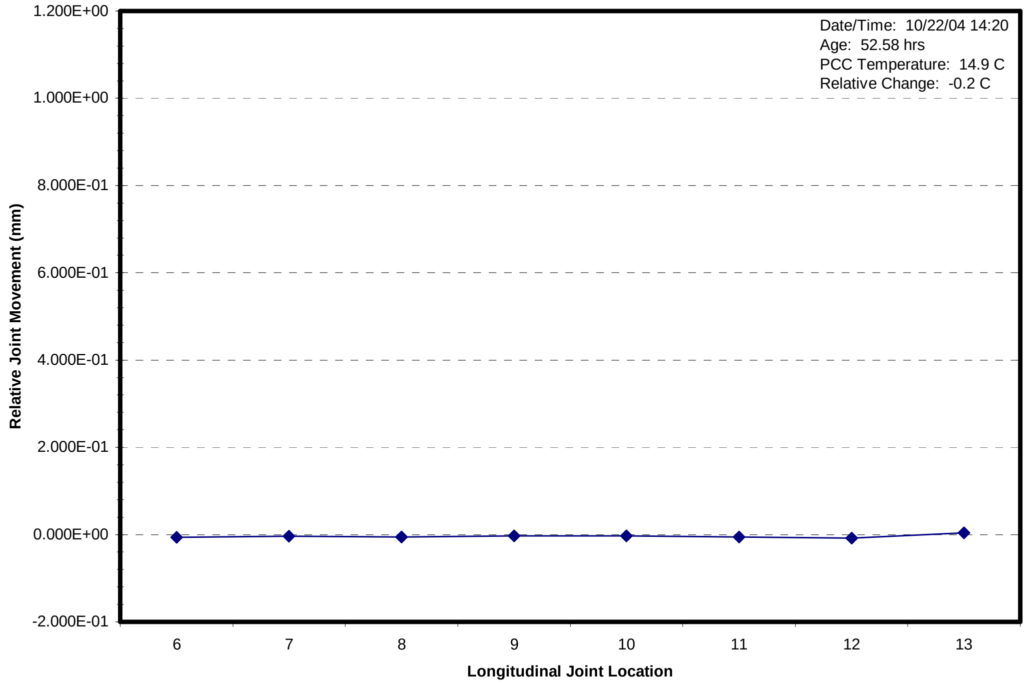

Figure B17. Longitudinal joint relative opening

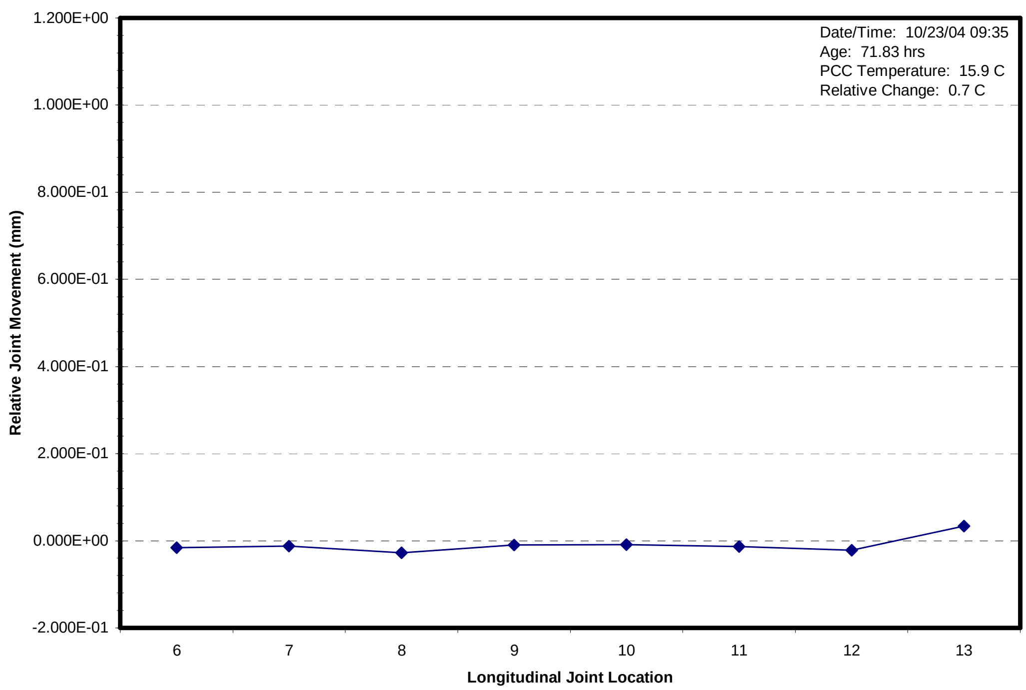

Figure B18. Longitudinal joint relative opening

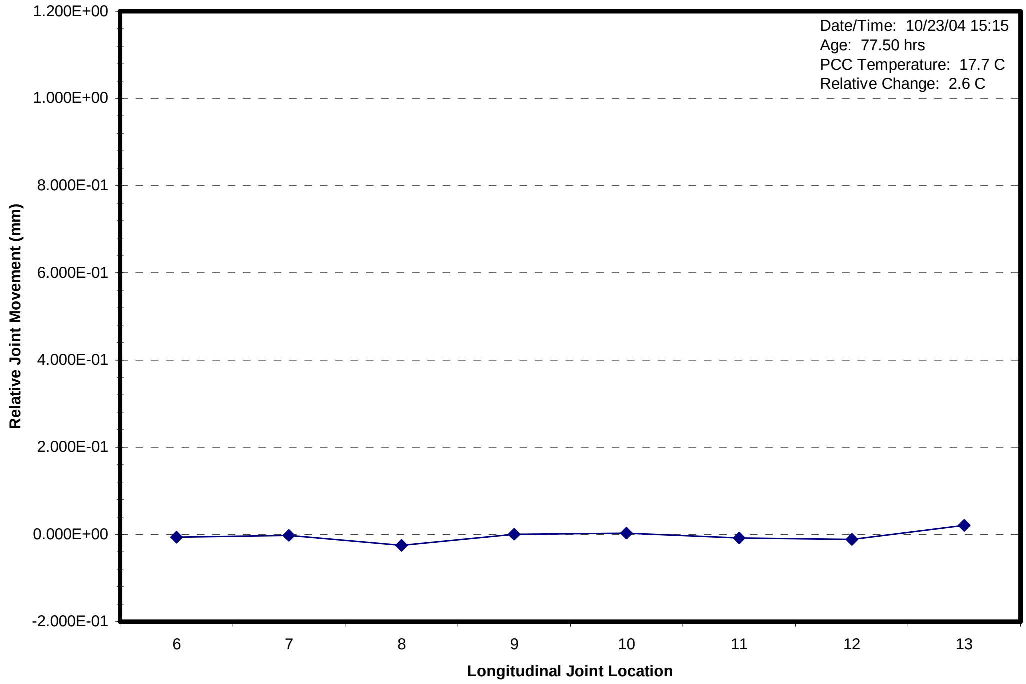

Figure B19. Longitudinal joint relative opening

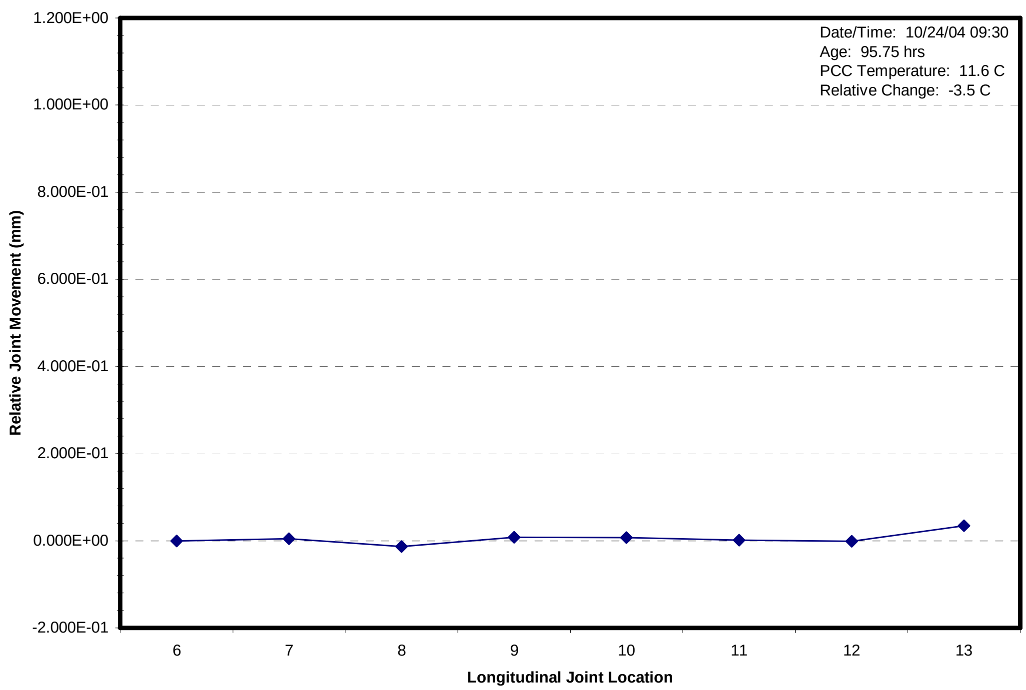

Figure B20. Longitudinal joint relative opening

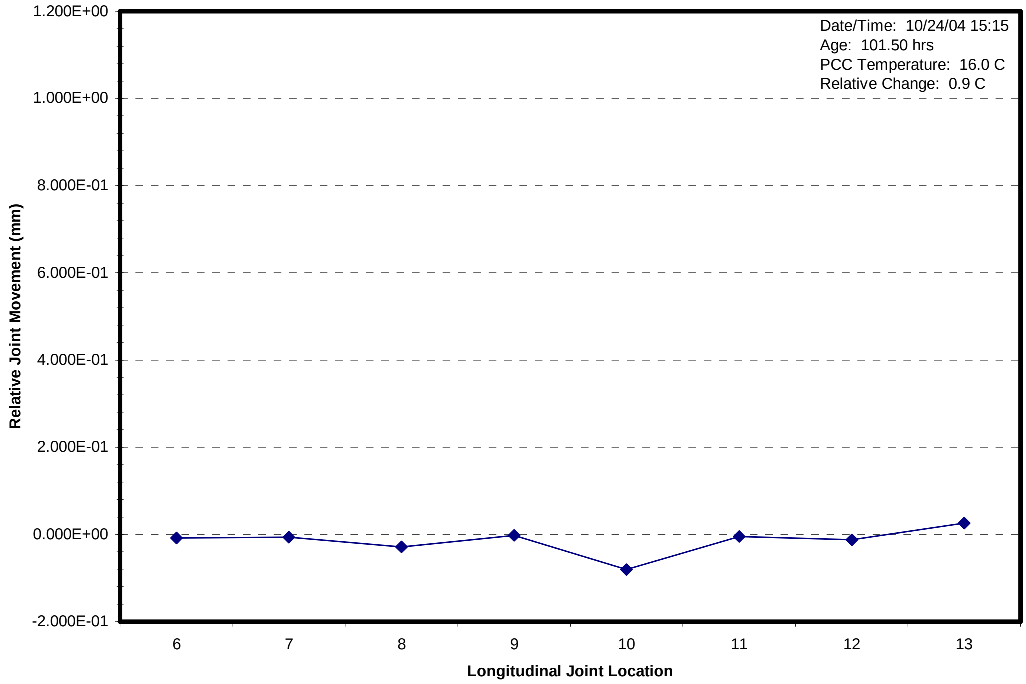

Figure B21. Longitudinal joint relative opening

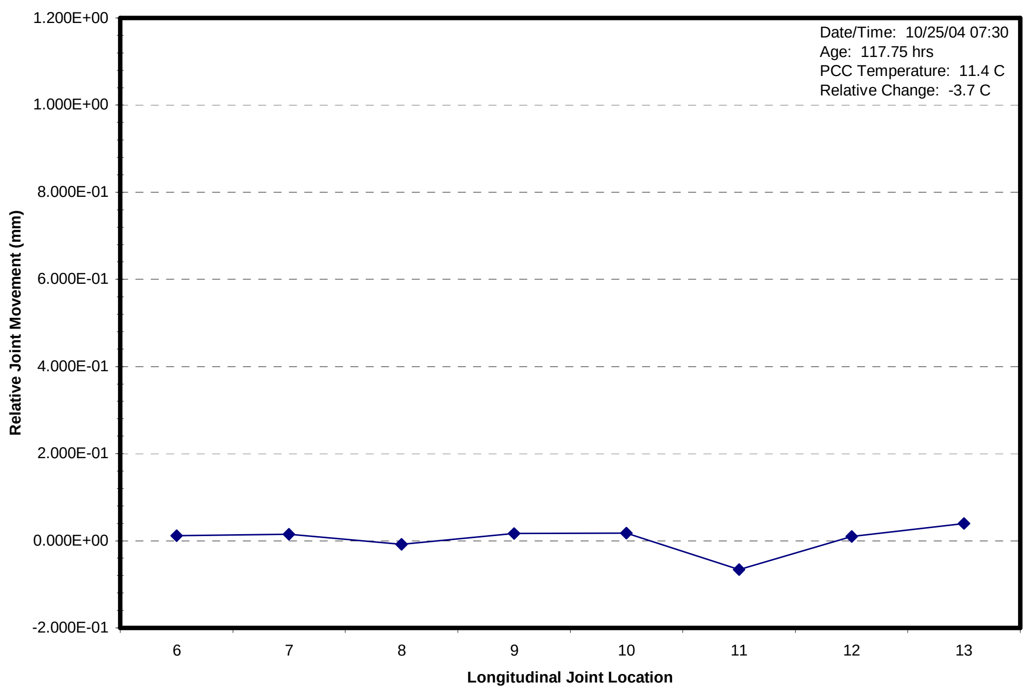

Figure B22. Longitudinal joint relative opening

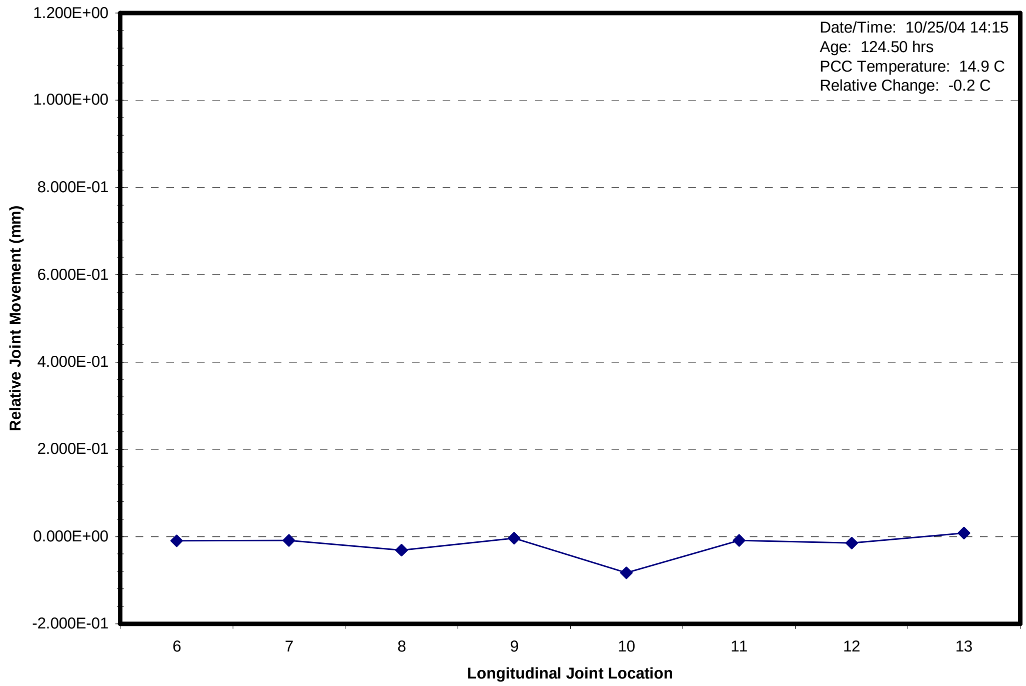

Figure B23. Longitudinal joint relative opening

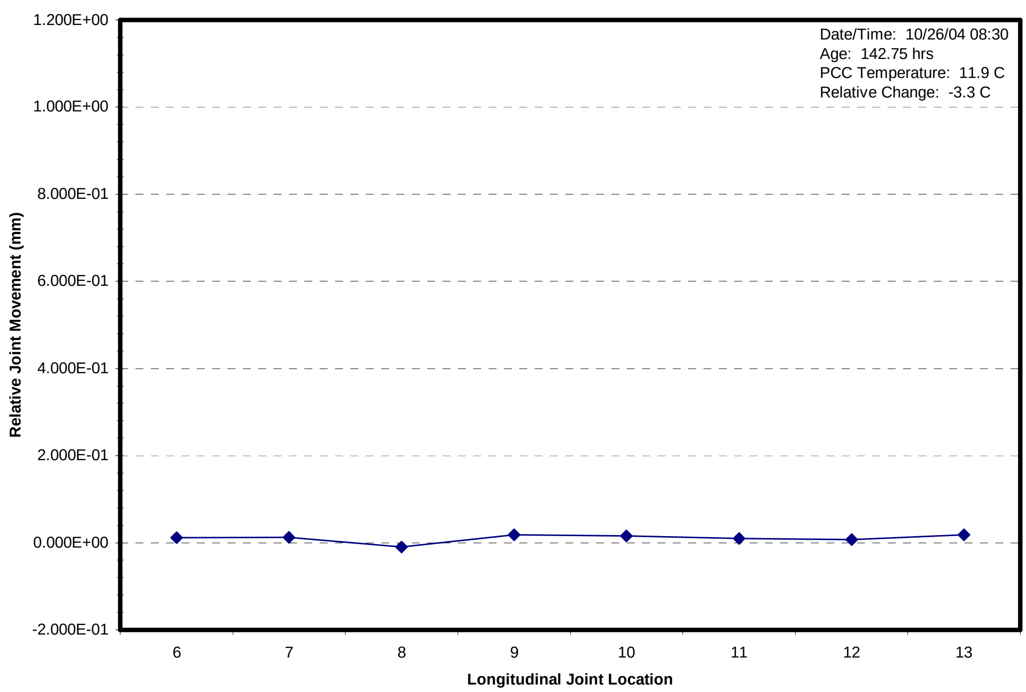

Figure B24. Longitudinal joint relative opening

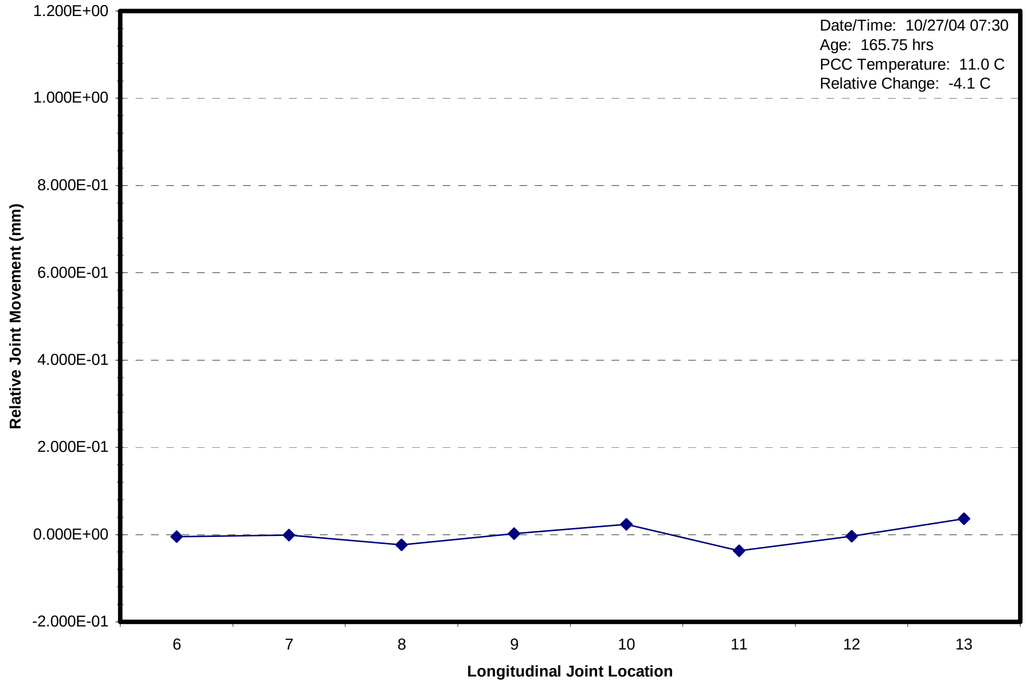

Figure B25. Longitudinal joint relative opening

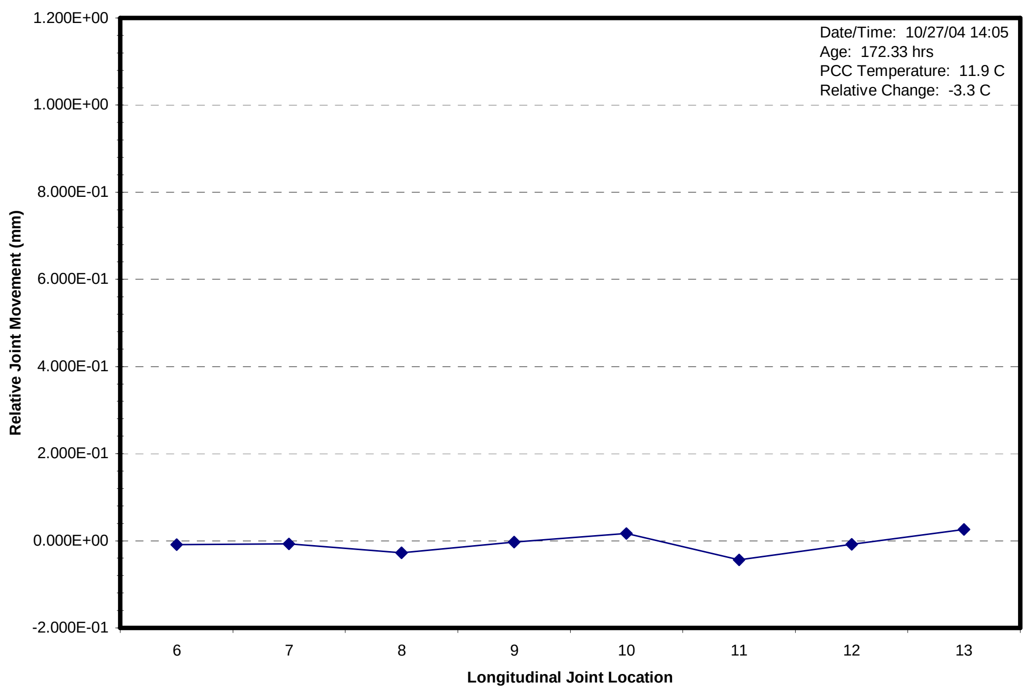

Figure B26. Longitudinal joint relative opening

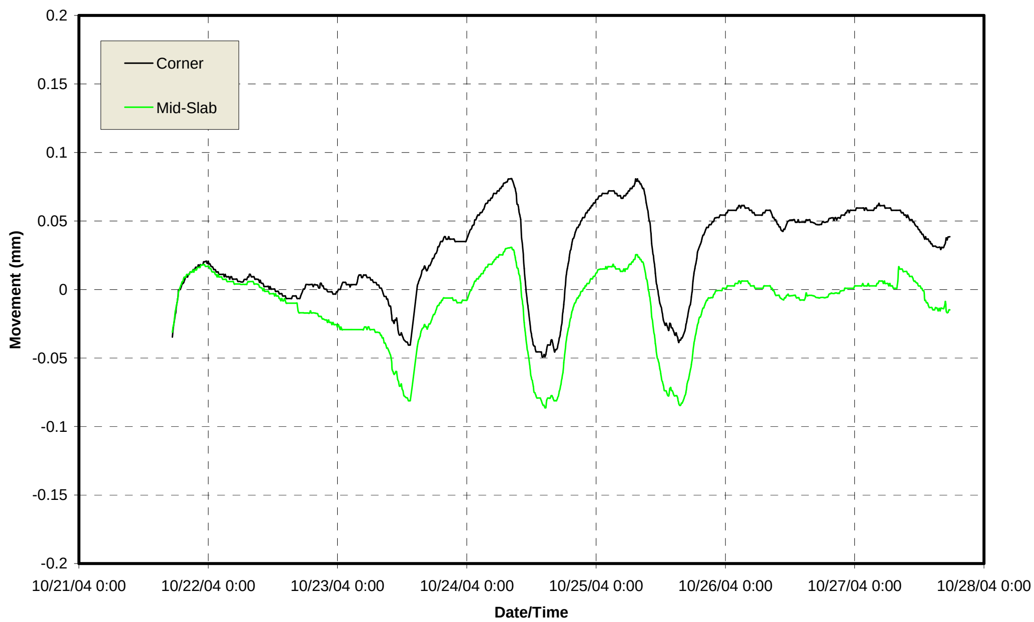

Figure B27. LVDT record

Table B1. Level A slab edge profile summary

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
1A121E	10/21/2004 7:00	21.25	19.5	8.0	93	151.4	3.41
1A122E	10/21/2004 10:30	24.75	18.9	10.2	96.1	172.7	3.23
1A31E	10/22/2004 6:00	44.25	15.4	10.4	94.8	175.6	3.21
1A33E	10/22/2004 13:00	51.25	14.8	11.6	92.9	172.8	3.23
1A41E	10/23/2004 7:30	69.75	15.6	16.9	100.6	145.3	3.46
1A43E	10/23/2004 13:00	75.25	17.3	18.4	98.4	149.8	3.43
1A51E	10/24/2004 9:00	95.25	11.6	7.6	97.2	150.4	3.42
1A53E	10/24/2004 14:00	100.25	15.1	16.7	98.6	150.6	3.42
1A61E	10/25/2004 6:30	116.75	11.6	8.2	96	143	3.48
1A63E	10/25/2004 13:10	123.42	13.9	16.1	96.5	146.9	3.45
1A71E	10/26/2004 8:30	142.75	11.8	9.5	93.3	148.2	3.44
1A81E	10/27/2004 6:45	165.00	10.9	9.2	94.5	144.4	3.47
1A83E	10/27/2004 13:00	171.25	11.6	10.9	94.4	147.1	3.45

Table B2. Level A mid-slab profile summary

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	RNPI (in/mi)	RN
1A122M	10/21/2004 10:30	24.75	18.9	10.2	70.7	120.9	3.68
1A41M	10/23/2004 7:30	69.75	15.6	16.9	83	127.3	3.63
1A43M	10/23/2004 13:00	75.25	17.3	18.4	73.8	114.3	3.75
1A51M	10/24/2004 9:00	95.25	11.6	7.6	76.5	116.9	3.72
1A53M	10/24/2004 14:00	100.25	15.1	16.7	78.1	114.7	3.74
1A61M	10/25/2004 6:30	116.75	11.6	8.2	73.3	117.7	3.71
1A63M	10/25/2004 13:10	123.42	13.9	16.1	73.3	106.4	3.82
1A71M	10/26/2004 8:30	142.75	11.8	9.5	72.4	108.3	3.8
1A81M	10/27/2004 6:45	165.00	10.9	9.2	78.7	111.4	3.77

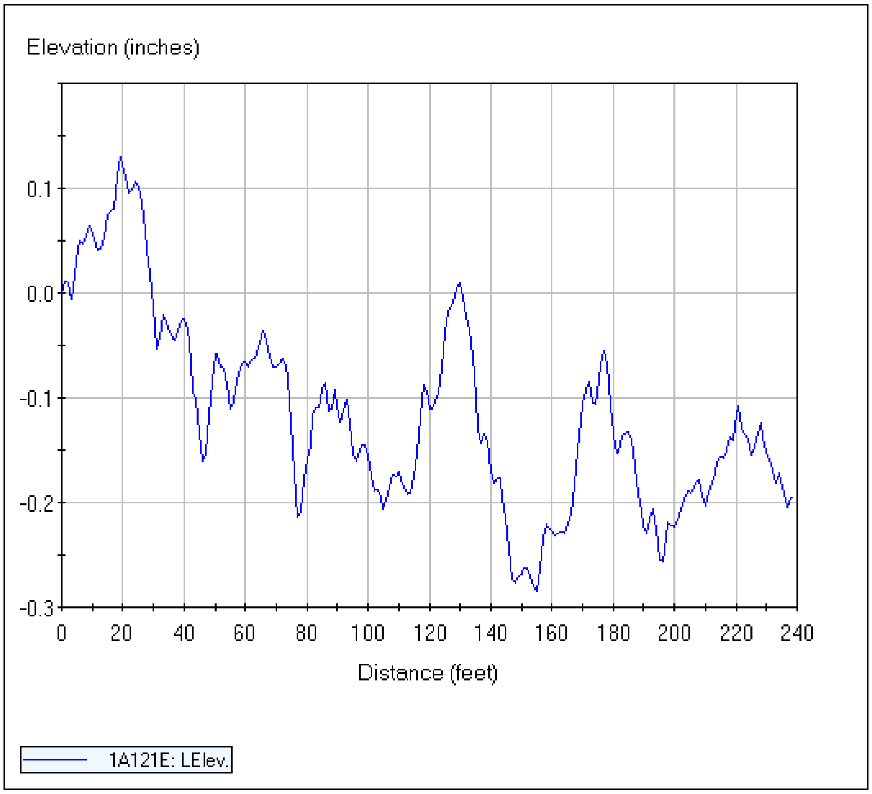

Figure B28. Level A profile, edge only, Oct. 21, 2004, 07:00

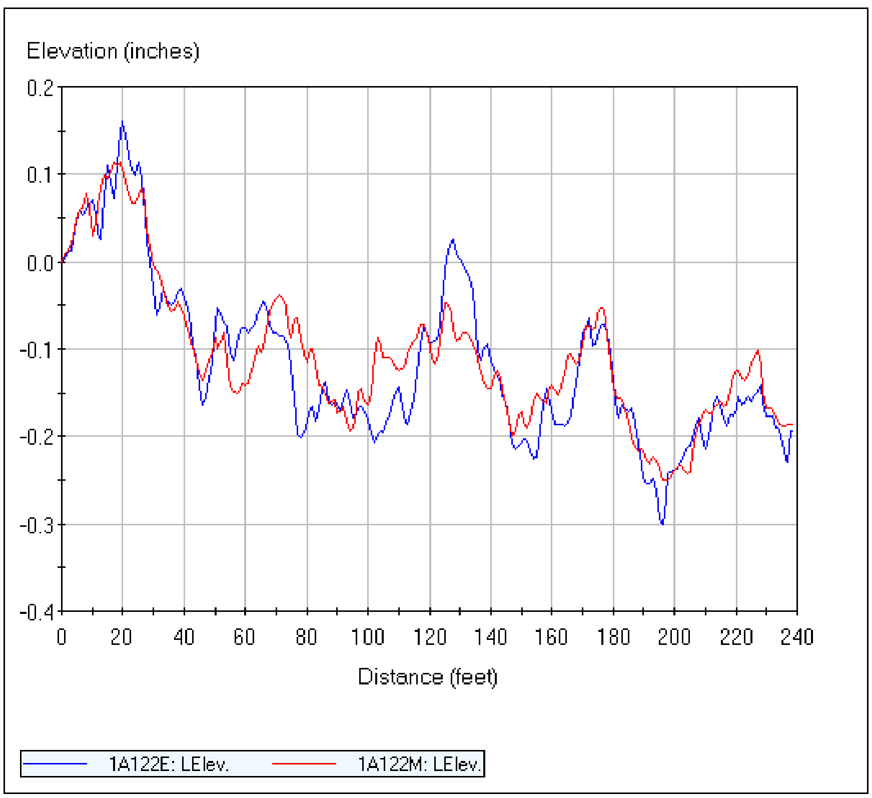

Figure B29. Level A profile, Oct. 21, 2004, 10:30

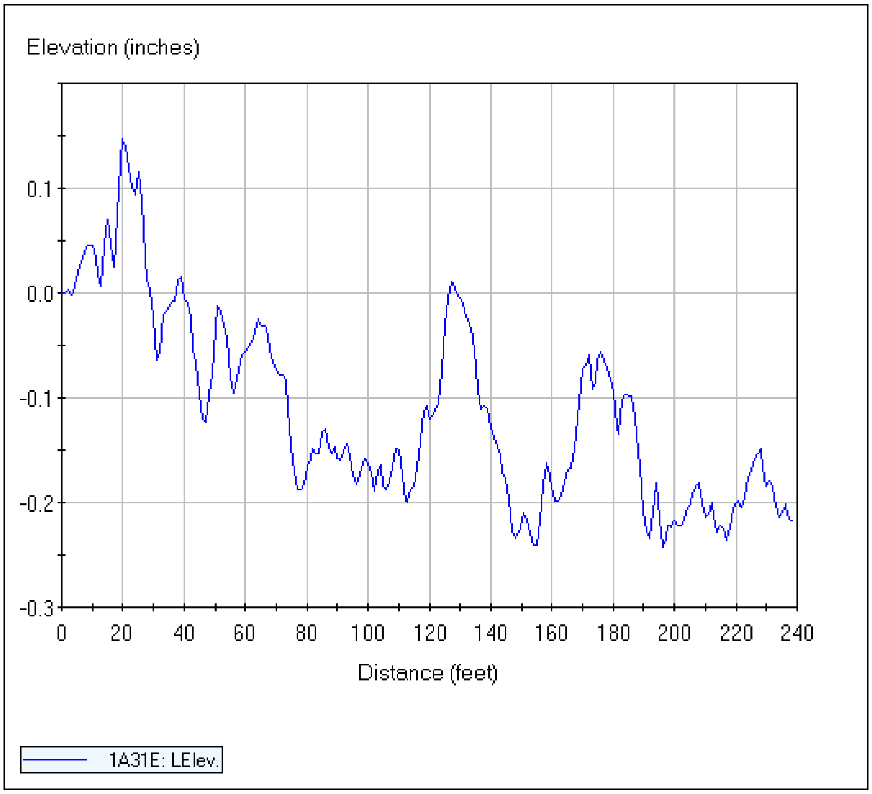

Figure B30. Level A profile, edge only, Oct. 22, 2004, 06:00

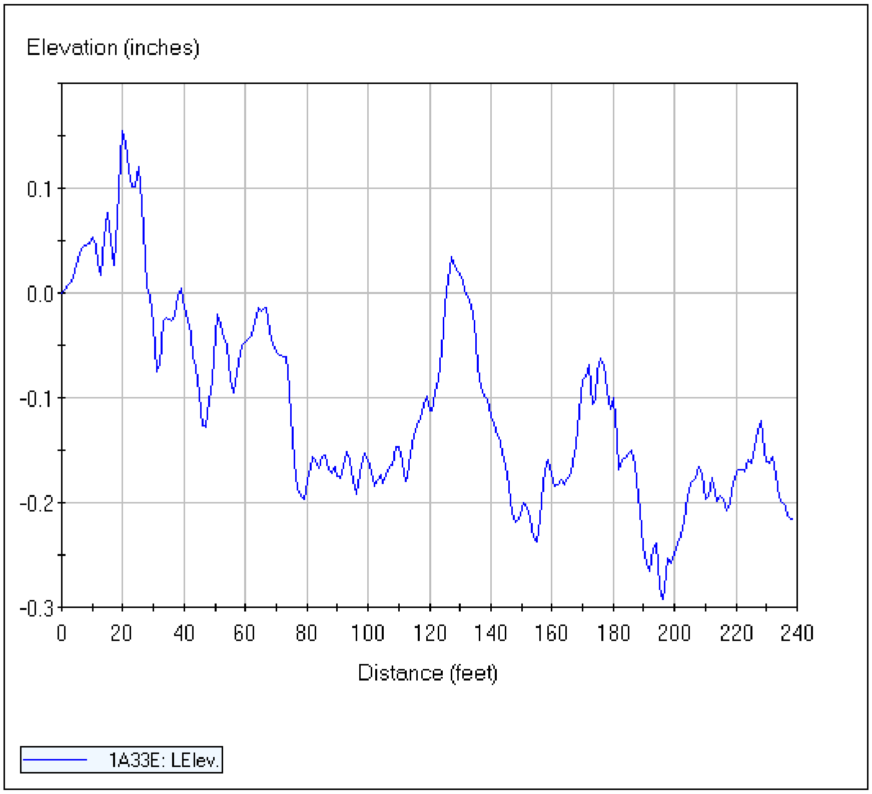

Figure B31. Level A profile, edge only, Oct. 22, 2004, 13:00

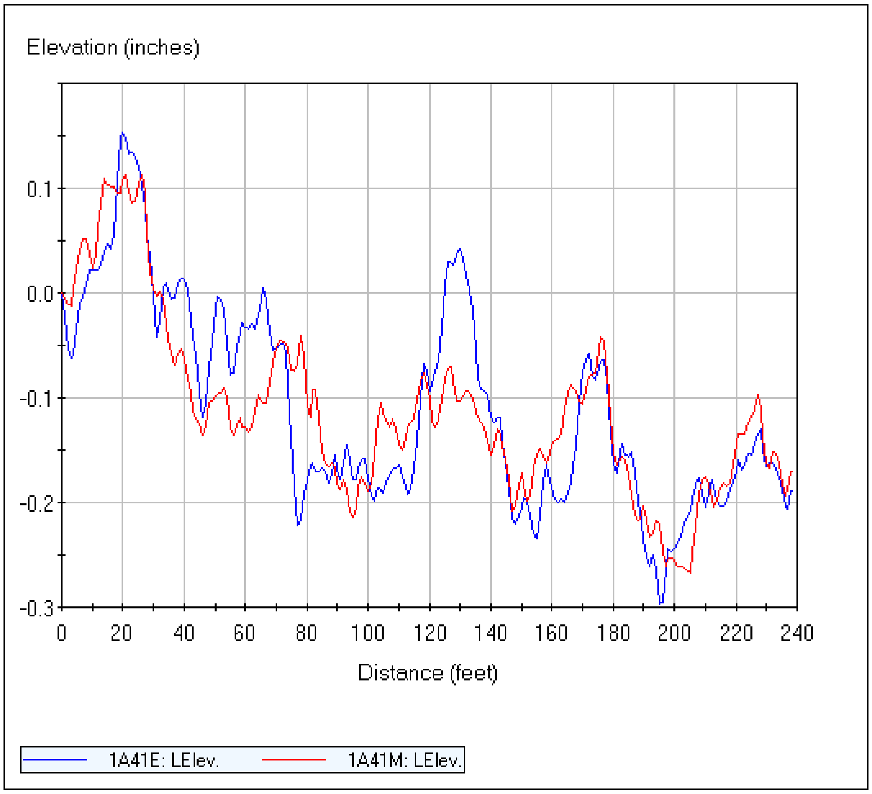

Figure B32. Level A profile, Oct. 23, 2004, 07:30

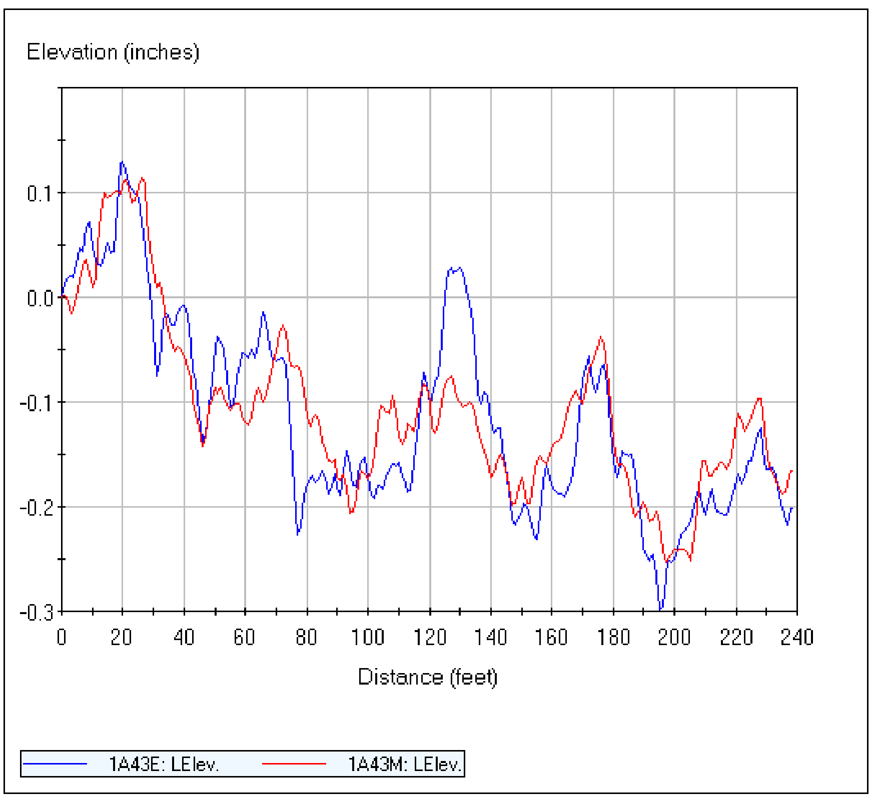

Figure B33. Level A profile, Oct. 23, 2004, 13:00

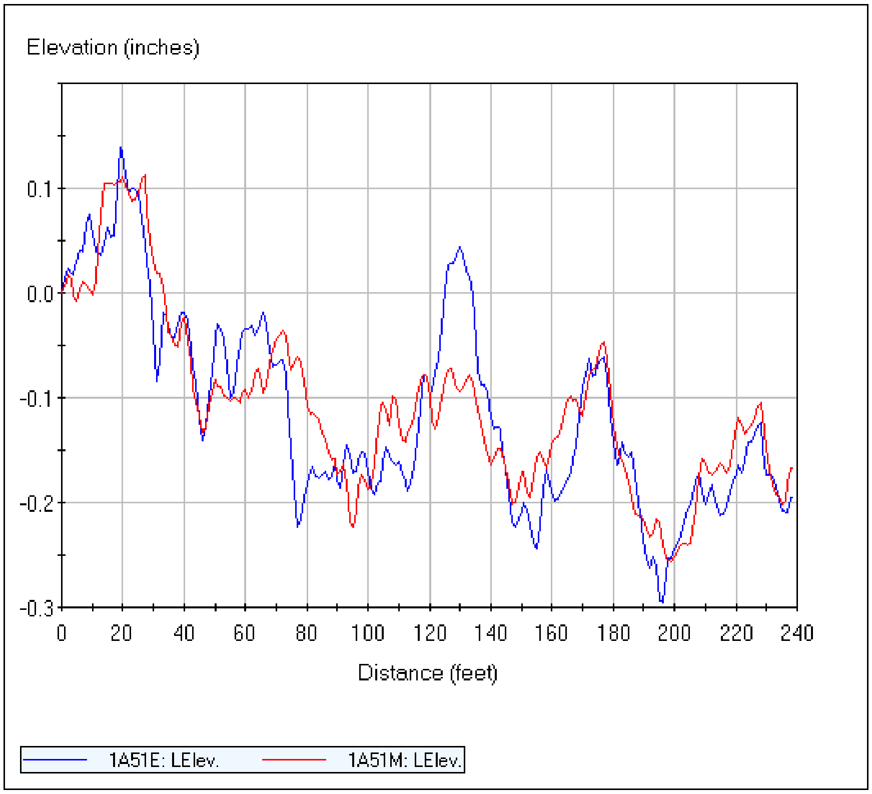

Figure B34. Level A profile, Oct. 24, 2004, 09:00

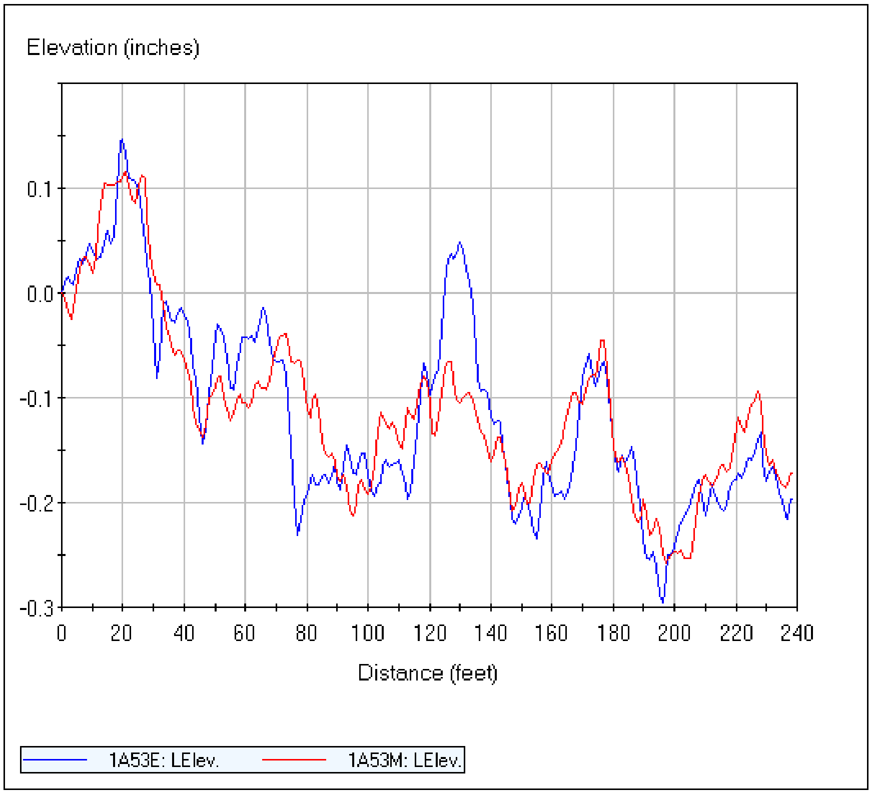

Figure B35. Level A profile, Oct. 23, 2004, 14:00

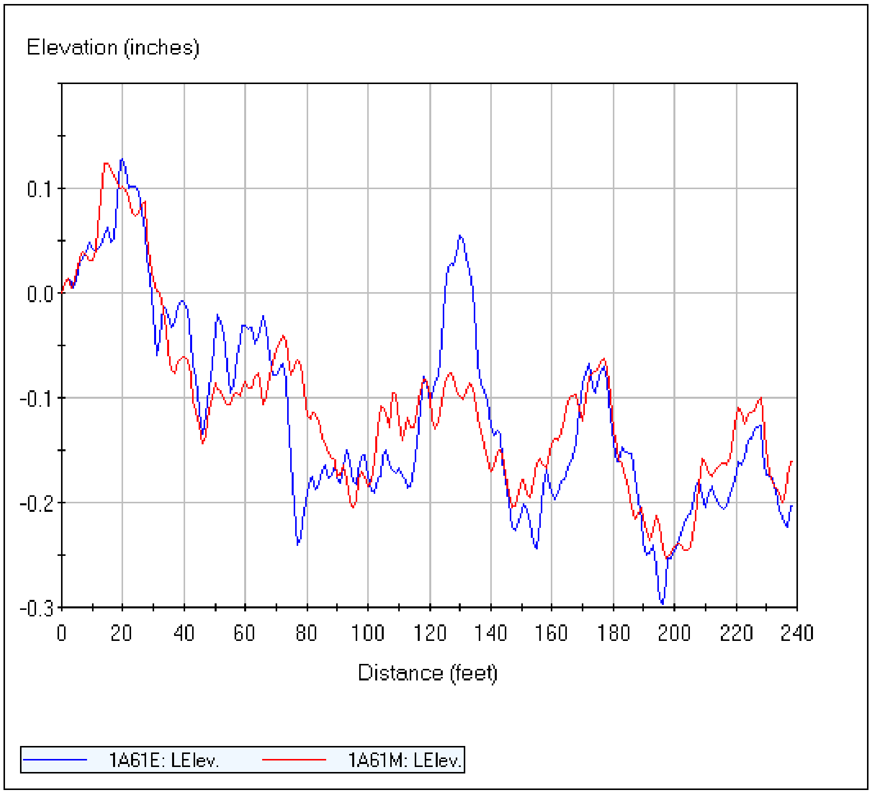

Figure B36. Level A profile, Oct. 25, 2004, 06:30

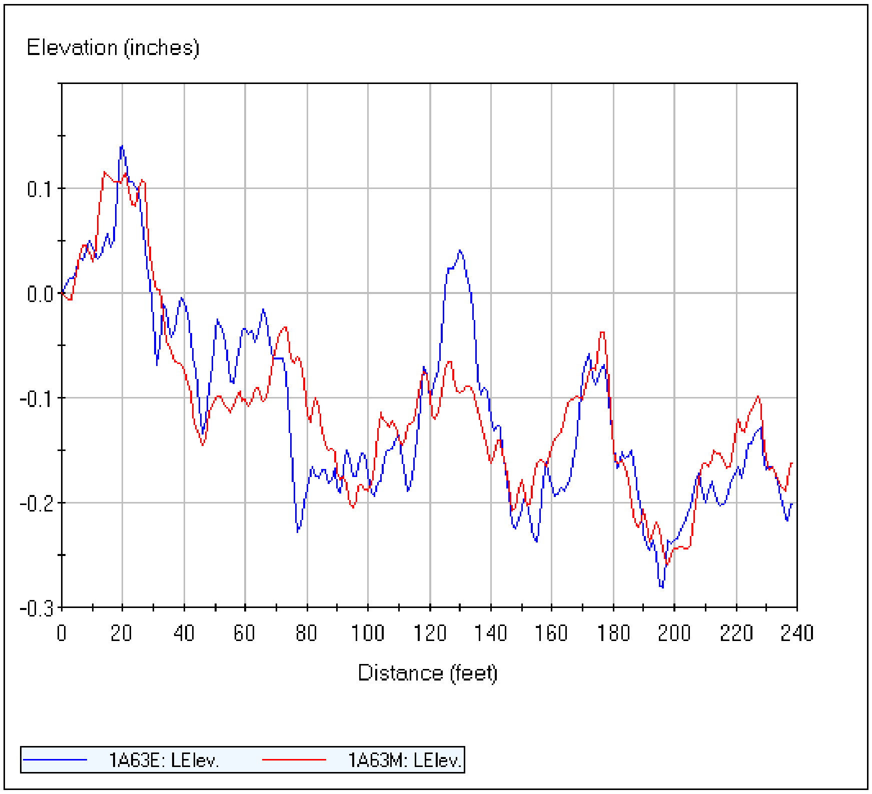

Figure B37. Level A profile, Oct. 25, 2004, 13:10

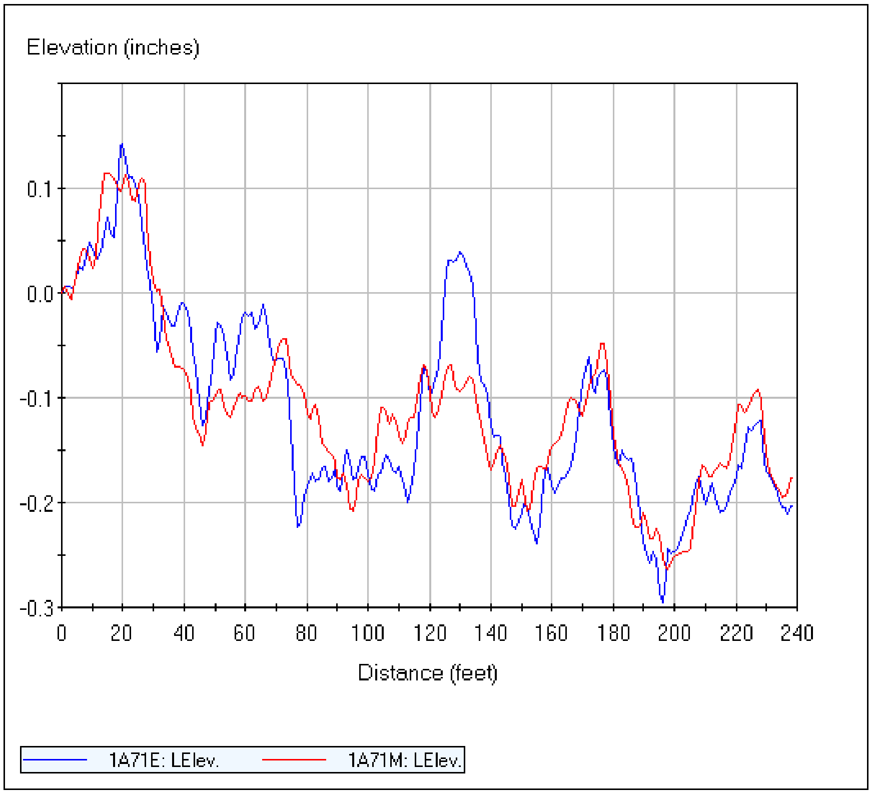

Figure B38. Level A profile, Oct. 26, 2004, 08:30

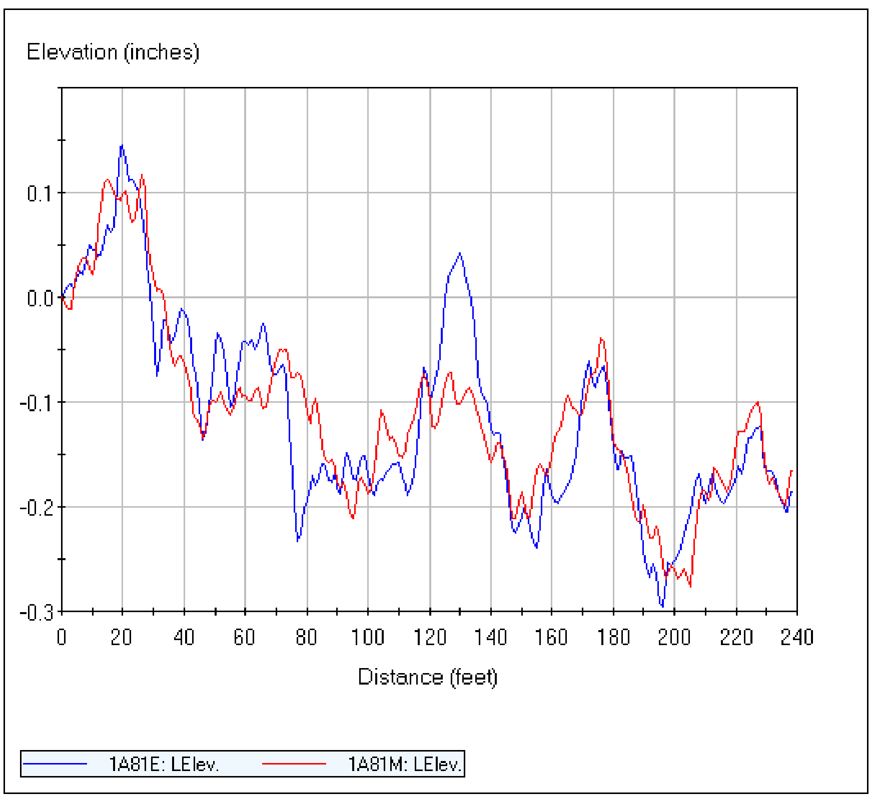

Figure B39. Level A profile, Oct. 27, 2004, 06:45

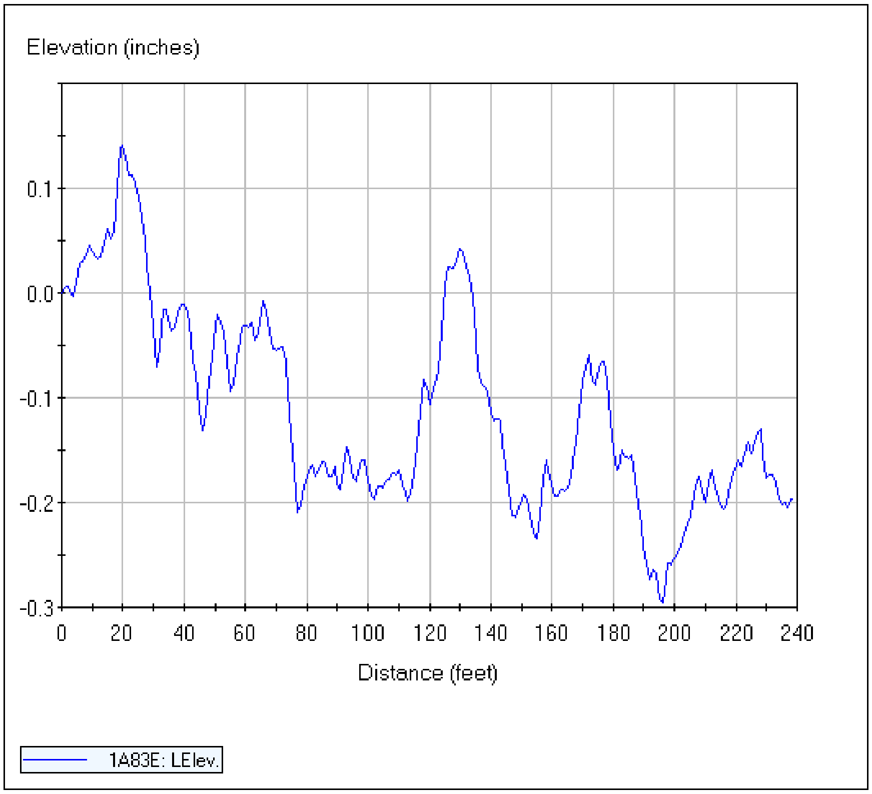

Figure B40. Level A profile, edge only, Oct. 27, 2004, 13:00

Table B3. Level B profile summary (1.5 ft from free edge)

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
1B143	10/23/2004 14:00	76.25	17.9	15.0	62.2	134.2	3.56
1B153	10/24/2004 15:00	101.25	15.8	17.8	71.1	115.6	3.73
1B163	10/25/2004 14:10	124.42	14.9	17.0	64.2	121.6	3.68
1B173	10/26/2004 14:00	148.25	12.1	9.6	64.2	128.6	3.61
1B183	10/27/2004 14:00	172.25	11.8	11.4	68.3	138.2	3.53

Table B4. Level B profile summary (3 ft from free edge)

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
1B243	10/23/2004 14:00	76.25	17.9	15.0	94.2	151.1	3.41
1B253	10/24/2004 15:00	101.25	15.8	17.8	96.9	166.4	3.28
1B263	10/25/2004 14:10	124.42	14.9	17.0	88.2	143	3.48
1B273	10/26/2004 14:00	148.25	12.1	9.6	83.8	142.8	3.49
1B283	10/27/2004 14:00	172.25	11.8	11.4	84.1	136.3	3.54

Table B5. Level B profile summary (3 ft from longitudinal joint)

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
1B343A	10/23/2004 14:00	76.25	17.9	15.0	109.5	157.3	3.36
1B353A	10/24/2004 15:00	101.25	15.8	17.8	121	177.3	3.2
1B363A	10/25/2004 14:10	124.42	14.9	17.0	117.3	180.3	3.17
1B373A	10/26/2004 14:00	148.25	12.1	9.6	122.1	167.7	3.27
1B383A	10/27/2004 14:00	172.25	11.8	11.4	120.8	170.8	3.25

Table B6. Level B profile summary (1 ft from longitudinal joint)

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
1B343B	10/23/2004 14:00	76.25	17.9	15.0	87.8	113.5	3.75
1B353B	10/24/2004 15:00	101.25	15.8	17.8	89.2	127.9	3.62
1B363B	10/25/2004 14:10	124.42	14.9	17.0	89.8	123	3.66
1B373B	10/26/2004 14:00	148.25	12.1	9.6	96.7	135.3	3.55
1B383B	10/27/2004 14:00	172.25	11.8	11.4	91.3	125.4	3.64

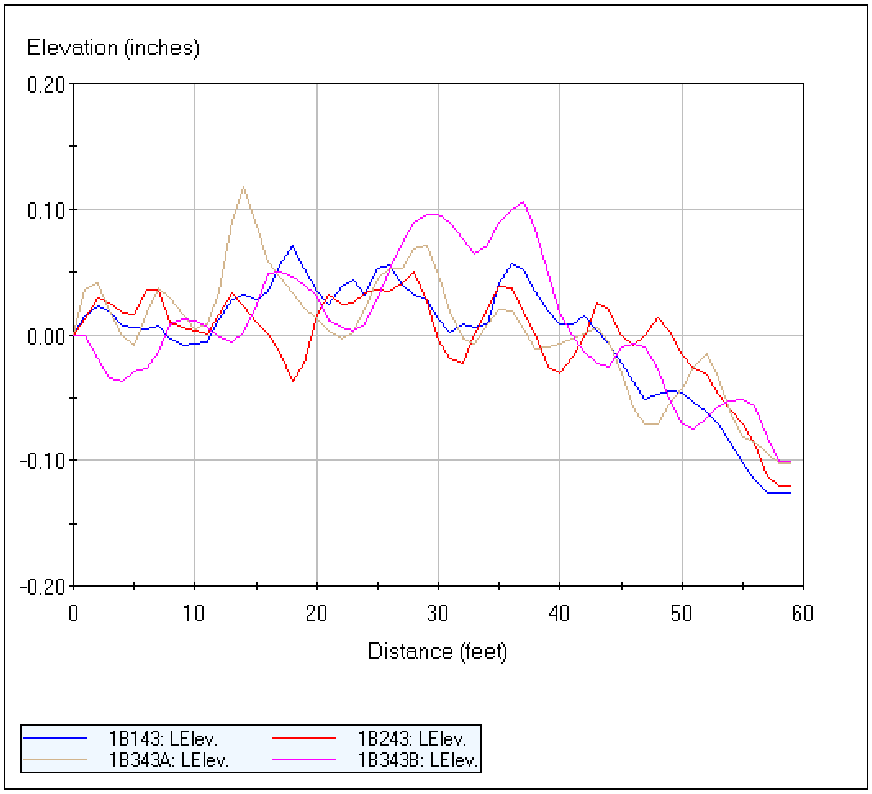

Figure B41. Level B profile, Oct. 23, 2004, 14:00

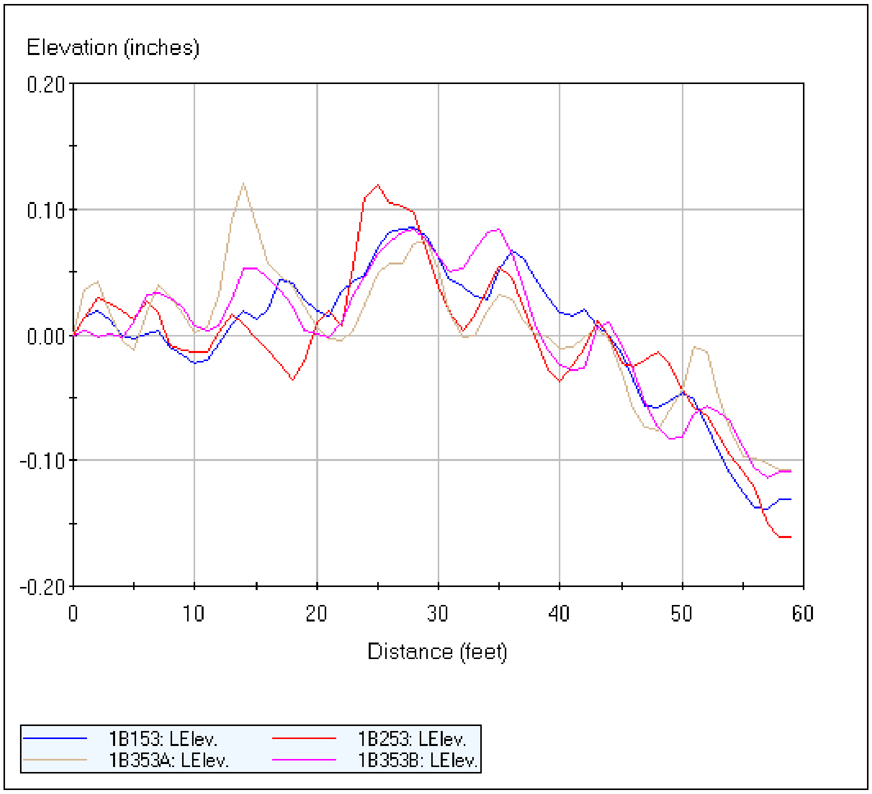

Figure B42. Level B profile, Oct. 24, 2004, 15:00

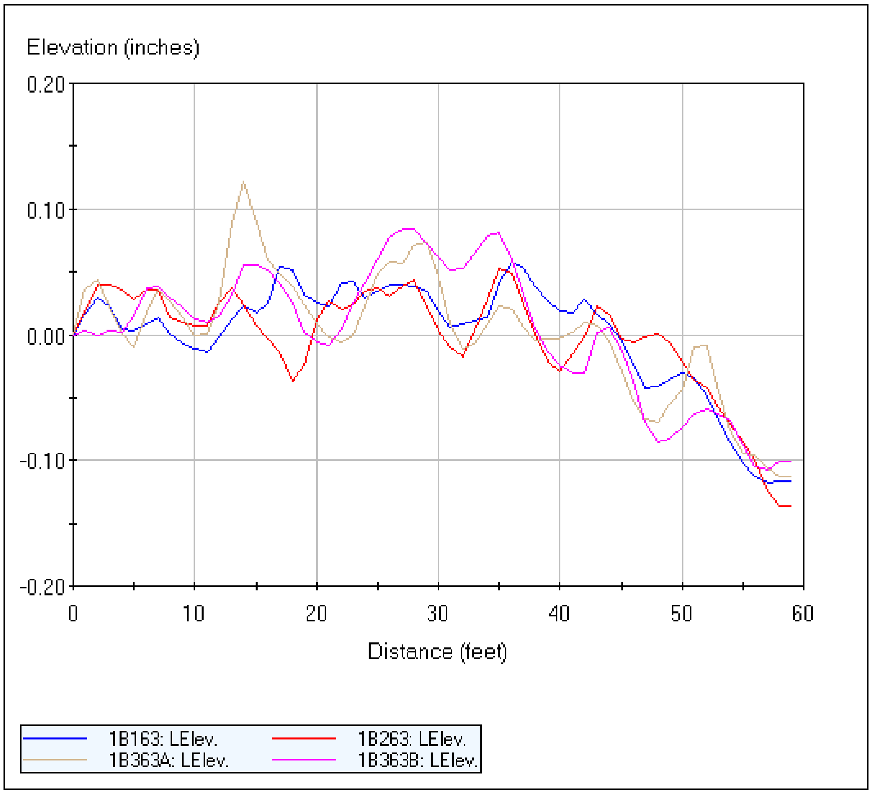

Figure B43. Level B profile, Oct. 25, 2004, 14:10

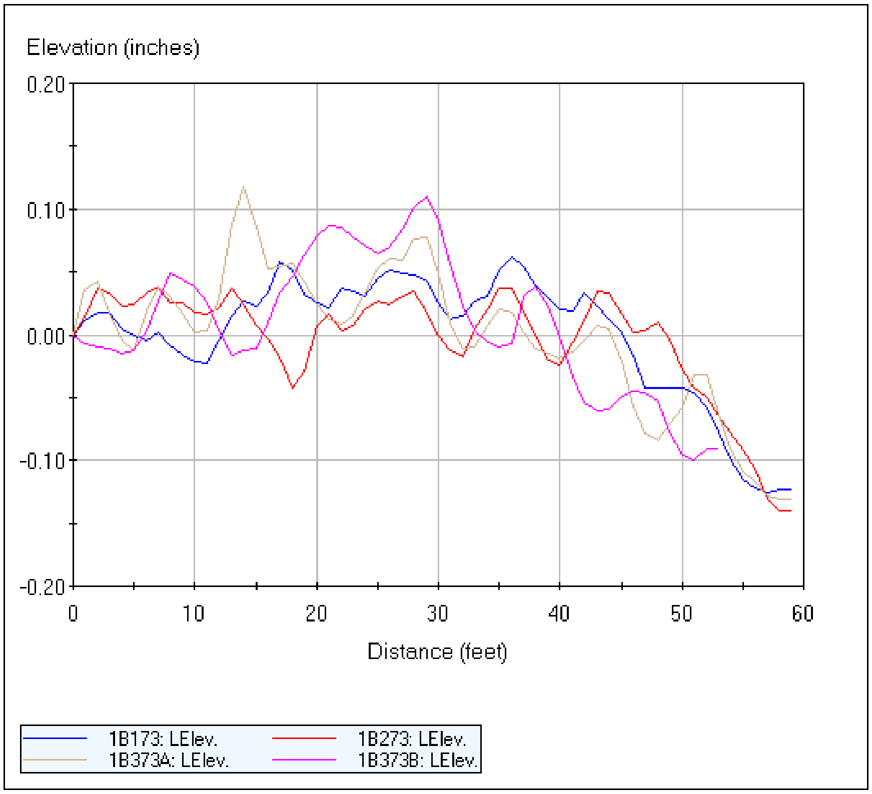

Figure B44. Level B profile, Oct. 26, 2004, 14:00

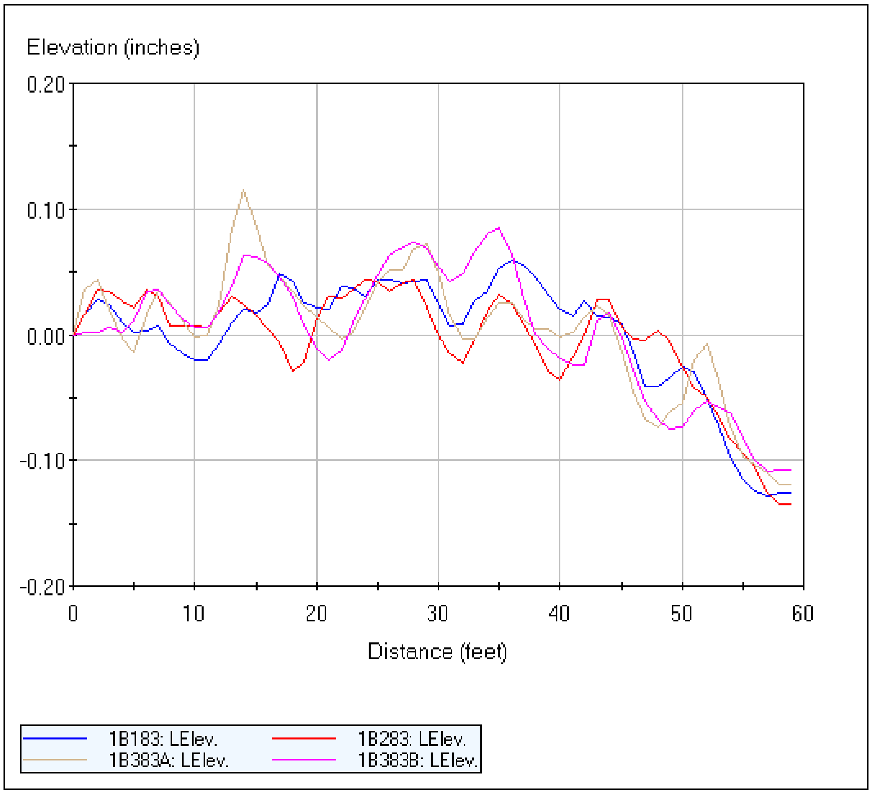

Figure B45. Level B profile, Oct. 27, 2004, 14:00

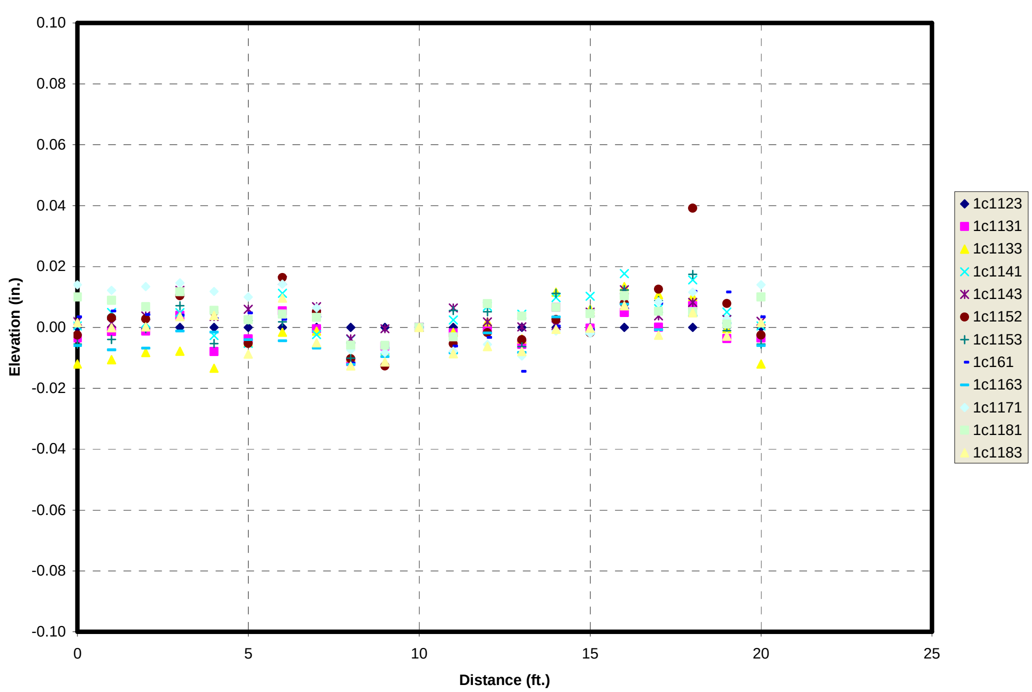

Figure B46. Level C profiles path 1, slab 8

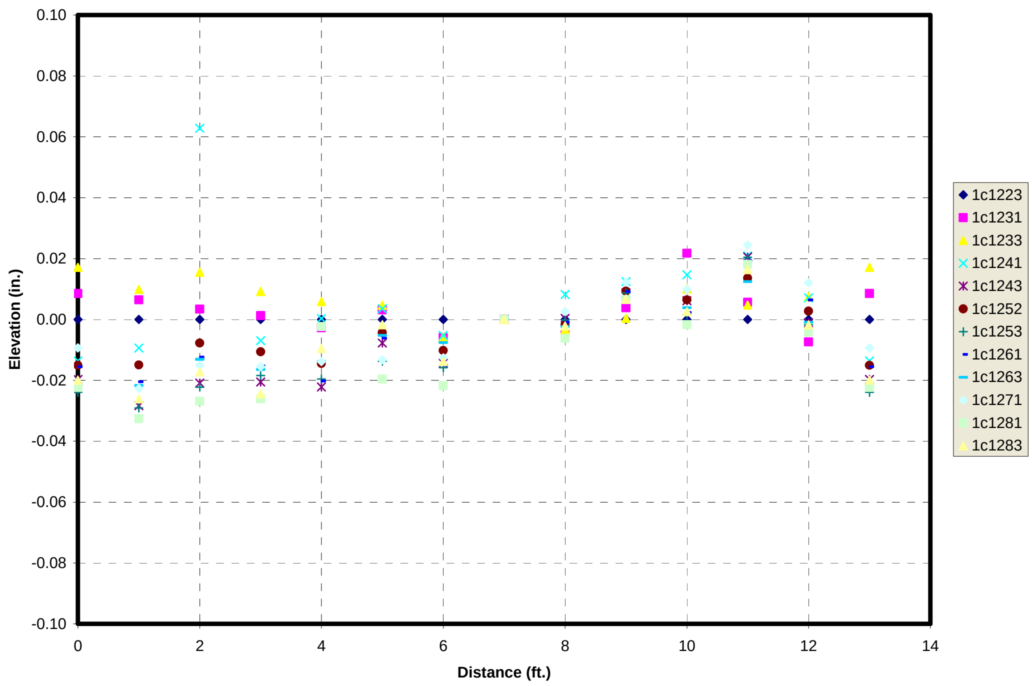

Figure B47. Level C profiles path 2, slab 8

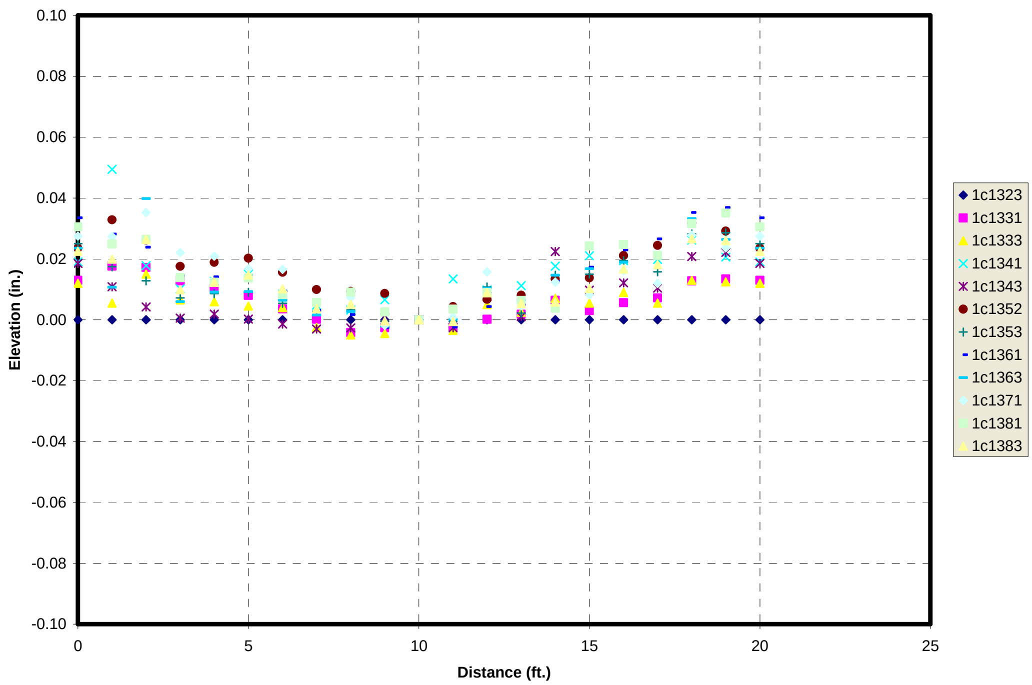

Figure B48. Level C profiles path 3, slab 8

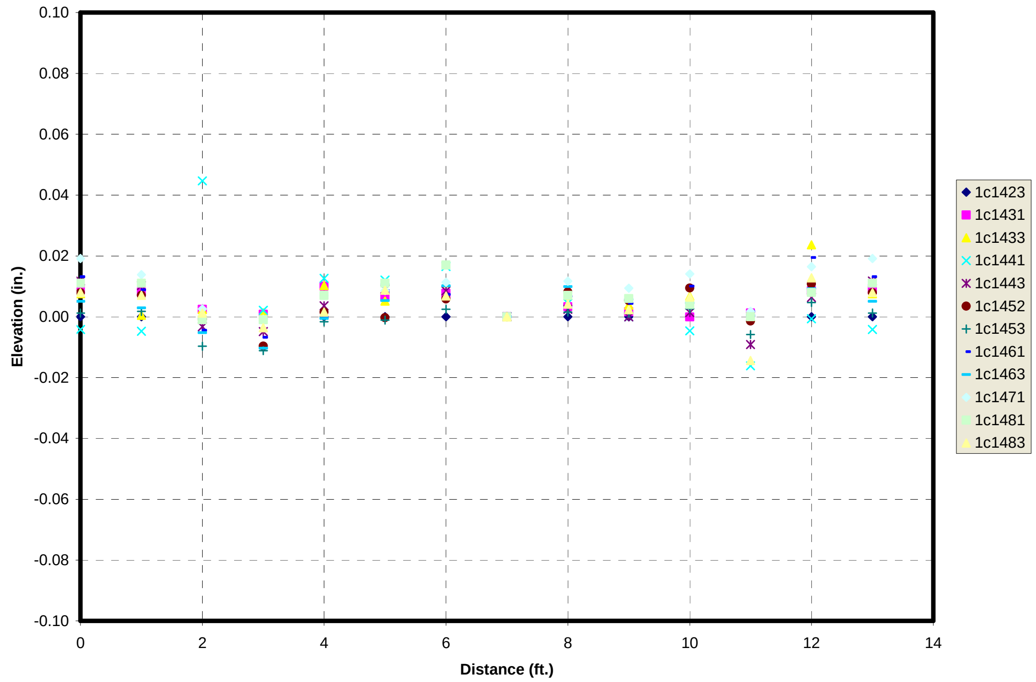

Figure B49. Level C profiles path 4, slab 8

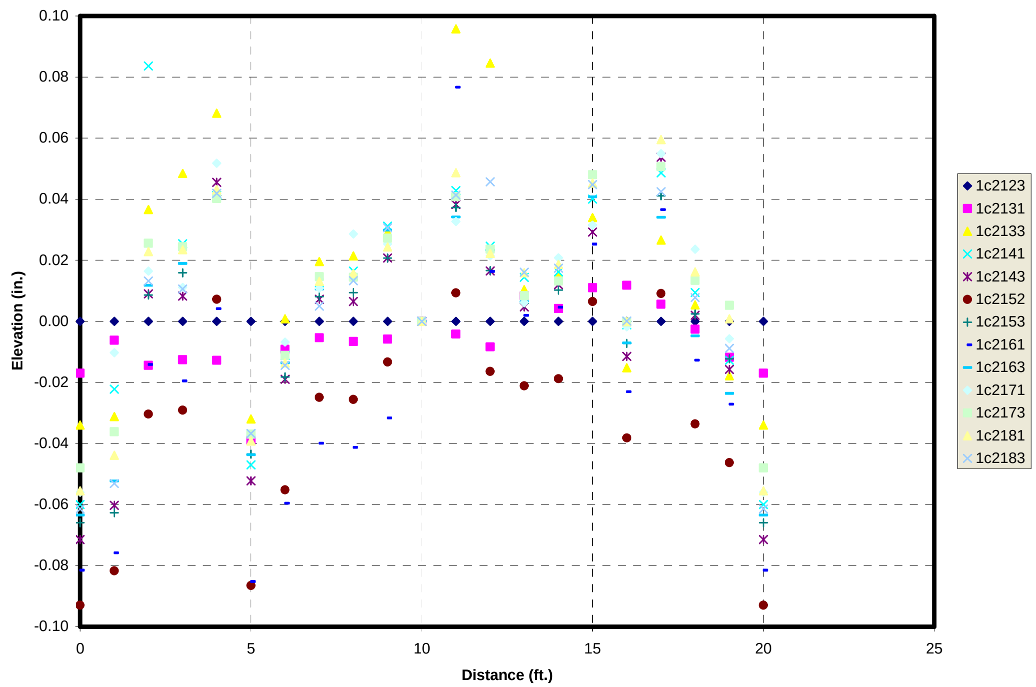

Figure B50. Level C profiles path 1, slab 9

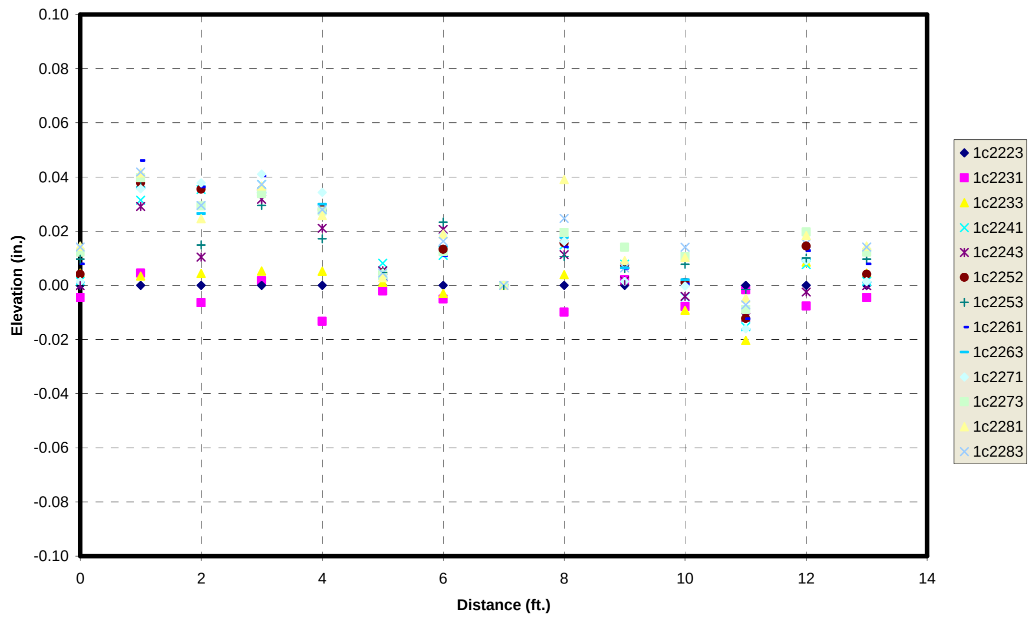

Figure B51. Level C profiles path 2, slab 9

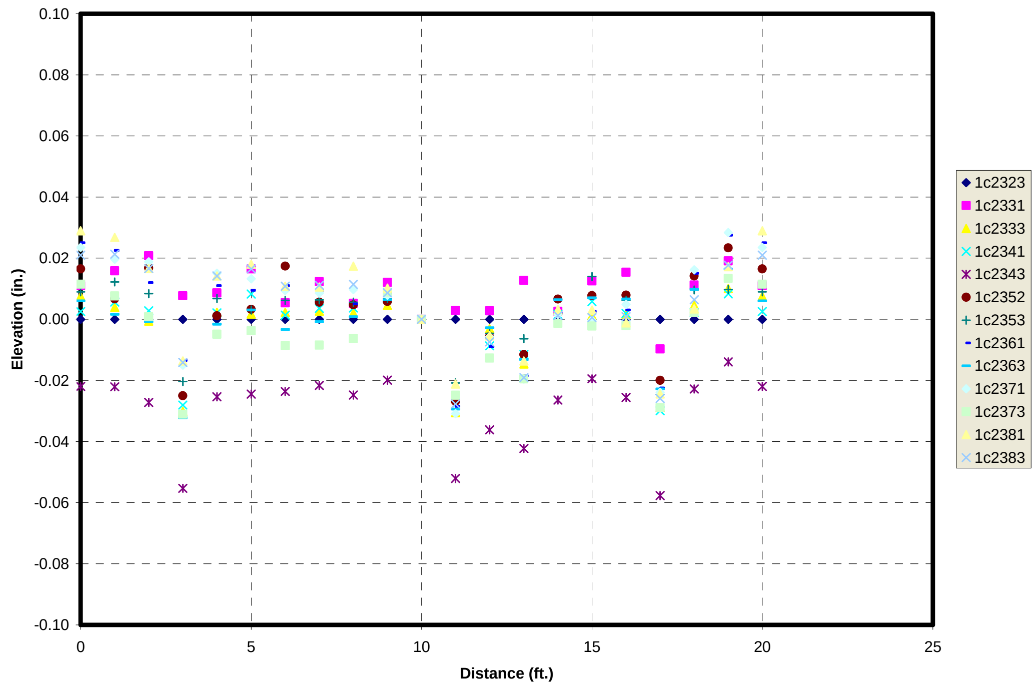

Figure B52. Level C profiles path 3, slab 9

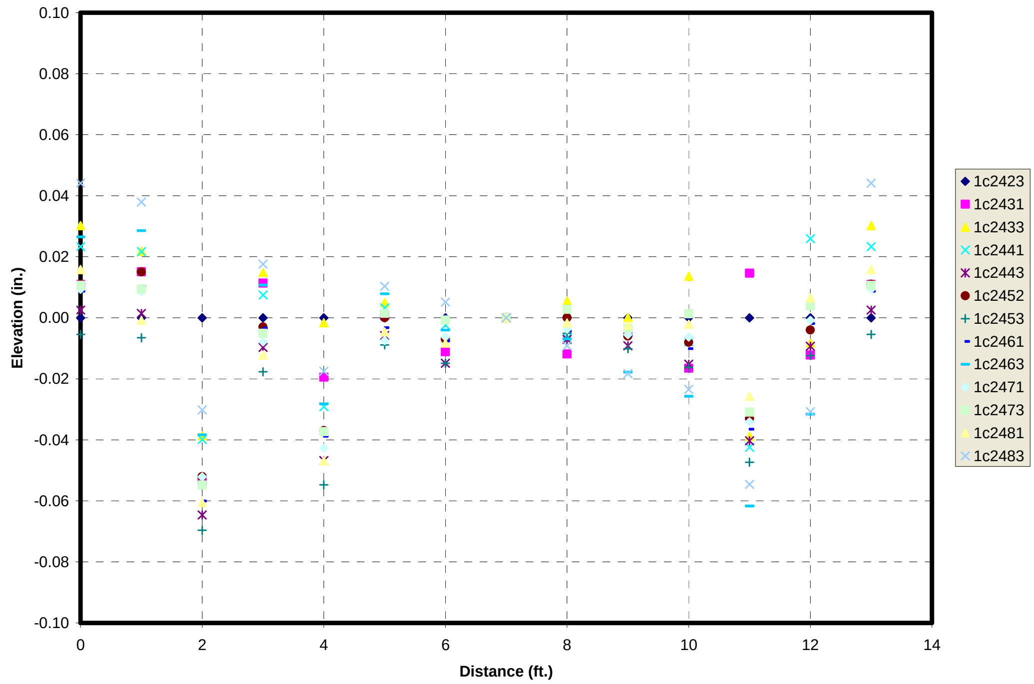

Figure B53. Level C profiles path 4, slab 9

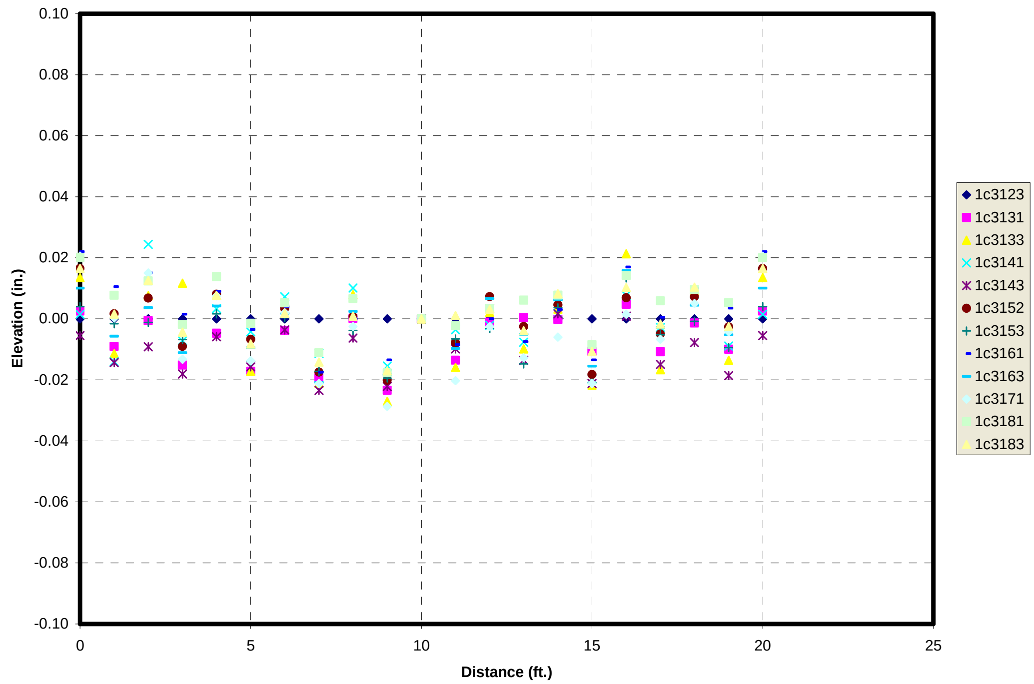

Figure B54. Level C profiles path 1, slab 10

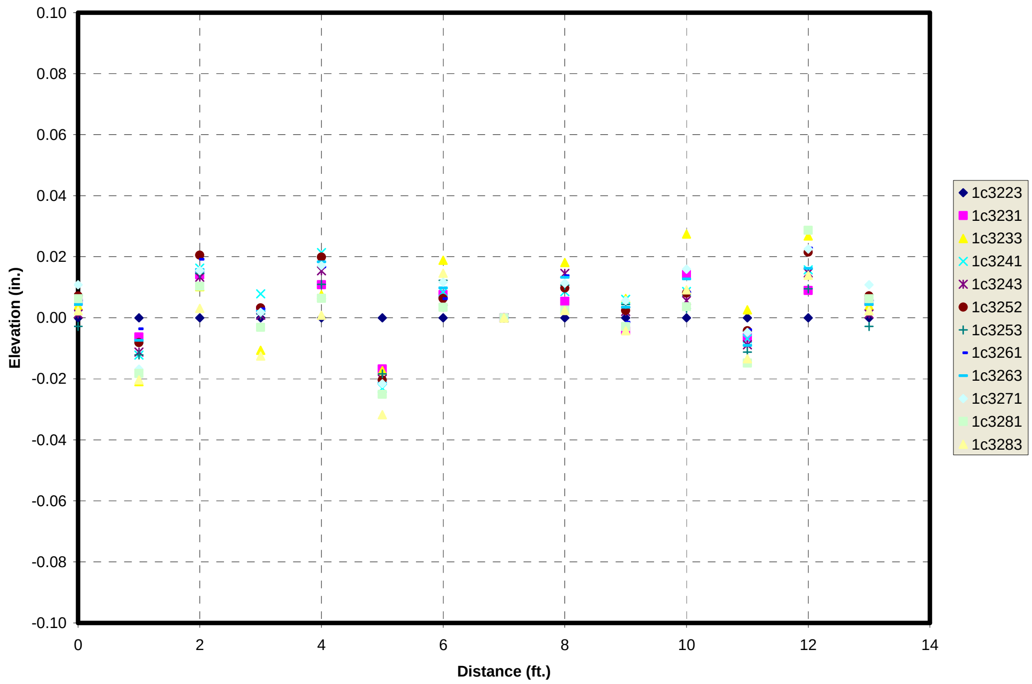

Figure B55. Level C profiles path 2, slab 10

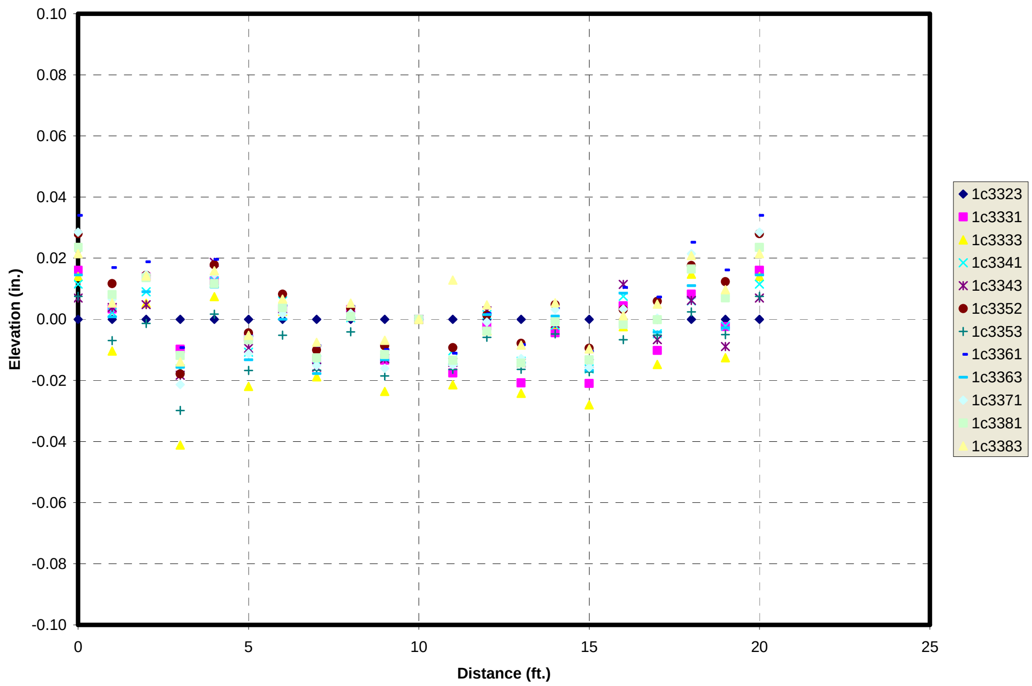

Figure B56. Level C profiles path 3, slab 10

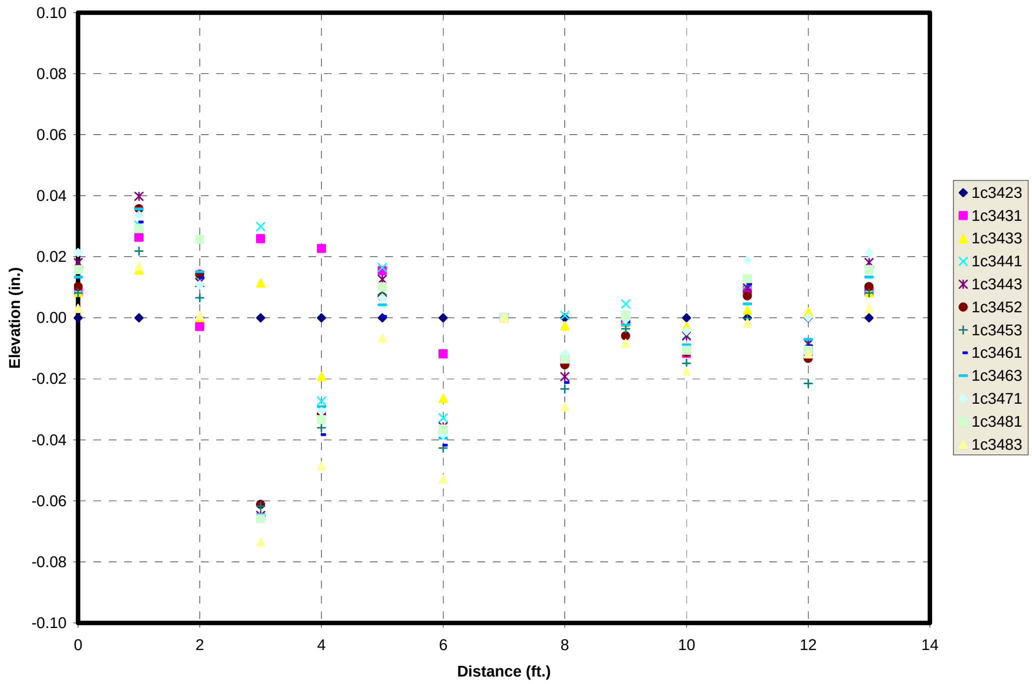

Figure B57. Level C profiles path 4, slab 10

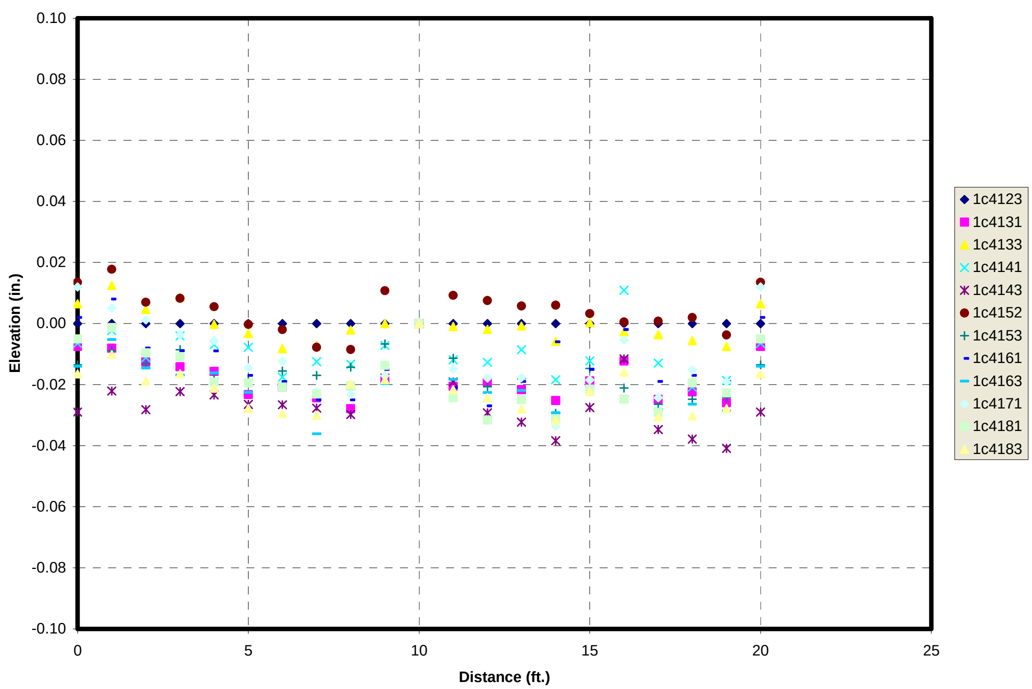

Figure B58. Level C profiles path 1, slab 11

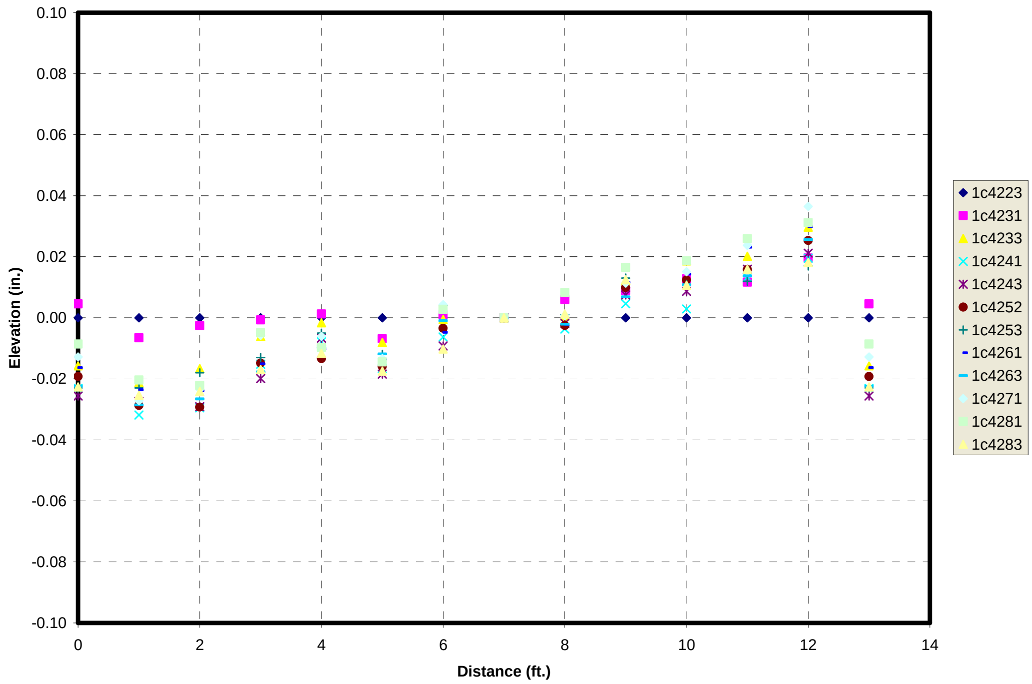

Figure B59. Level C profiles path 2, slab 11

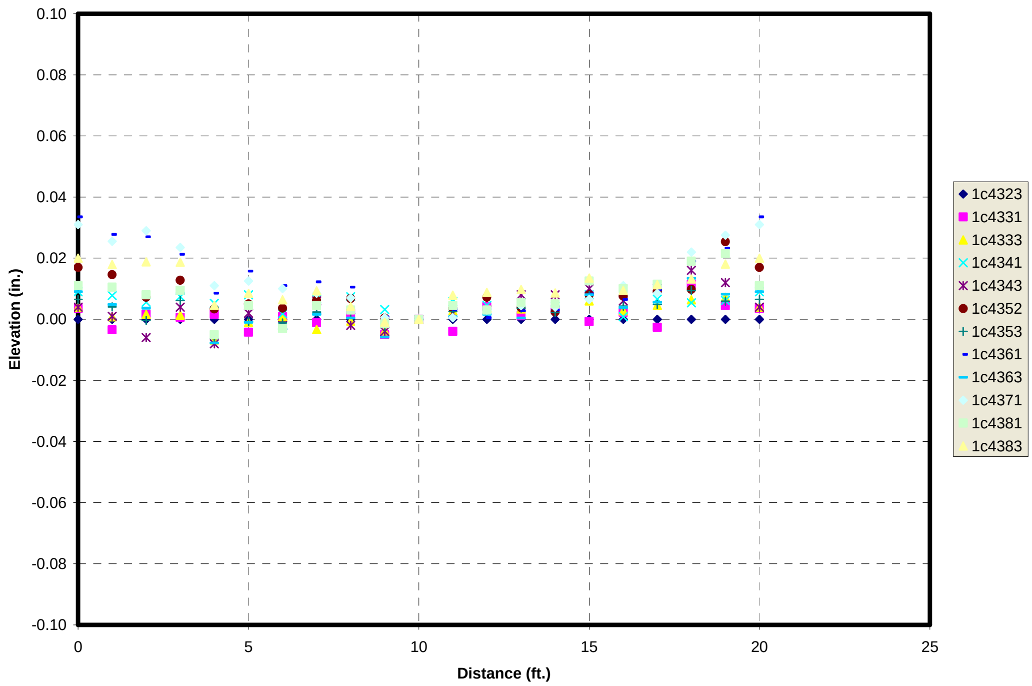

Figure B60. Level C profiles path 3, slab 11

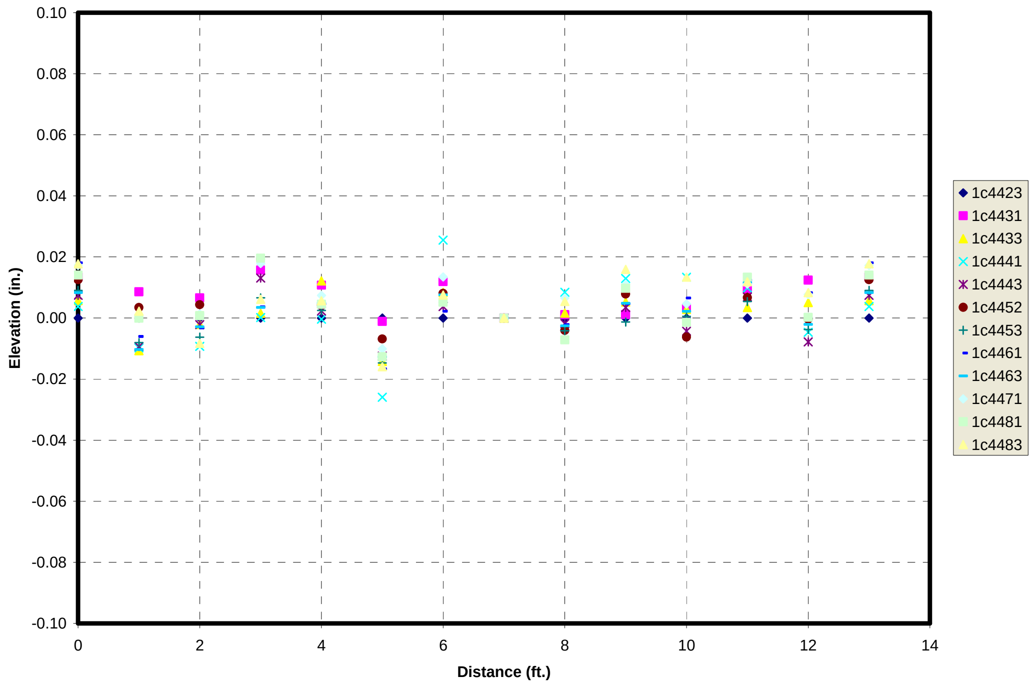

Figure B61. Level C profiles path 4, slab 11

APPENDIX C. AFTERNOON PAVING TEST SECTION

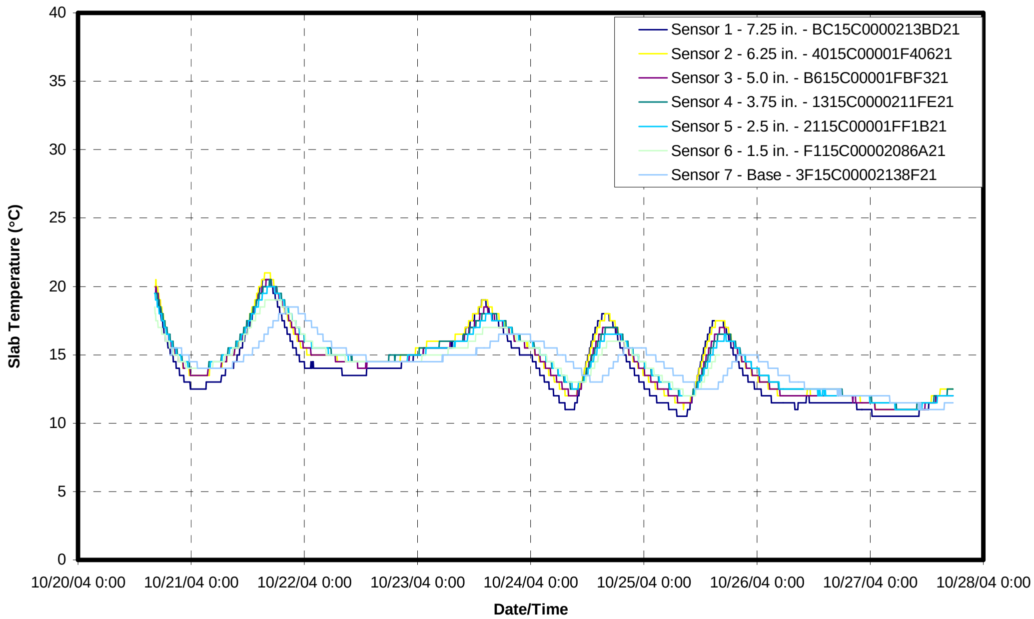

Figure C1. Slab temperature data

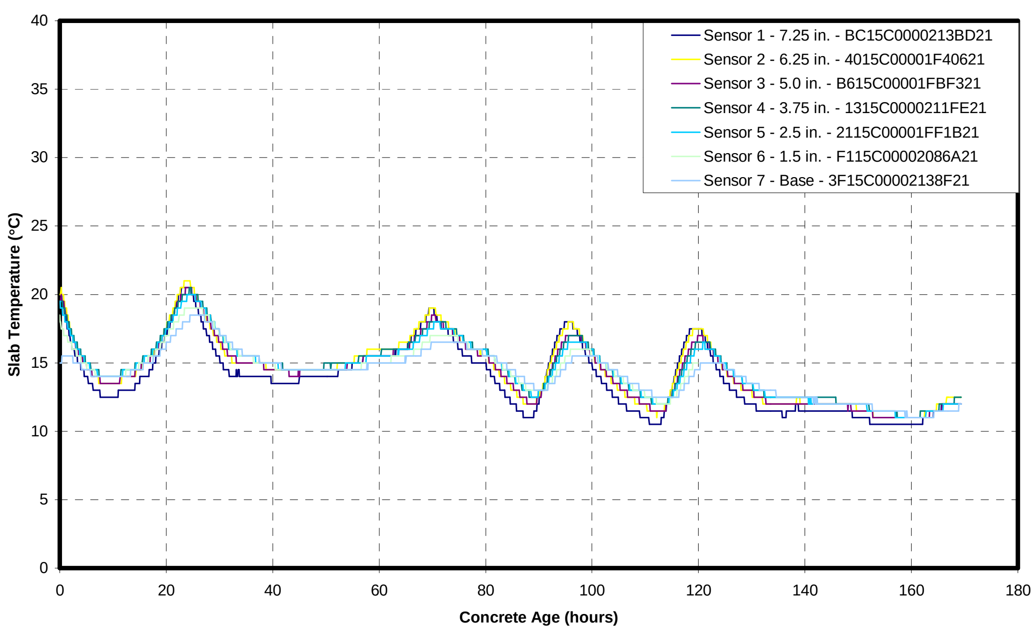

Figure C2. Slab temperature data

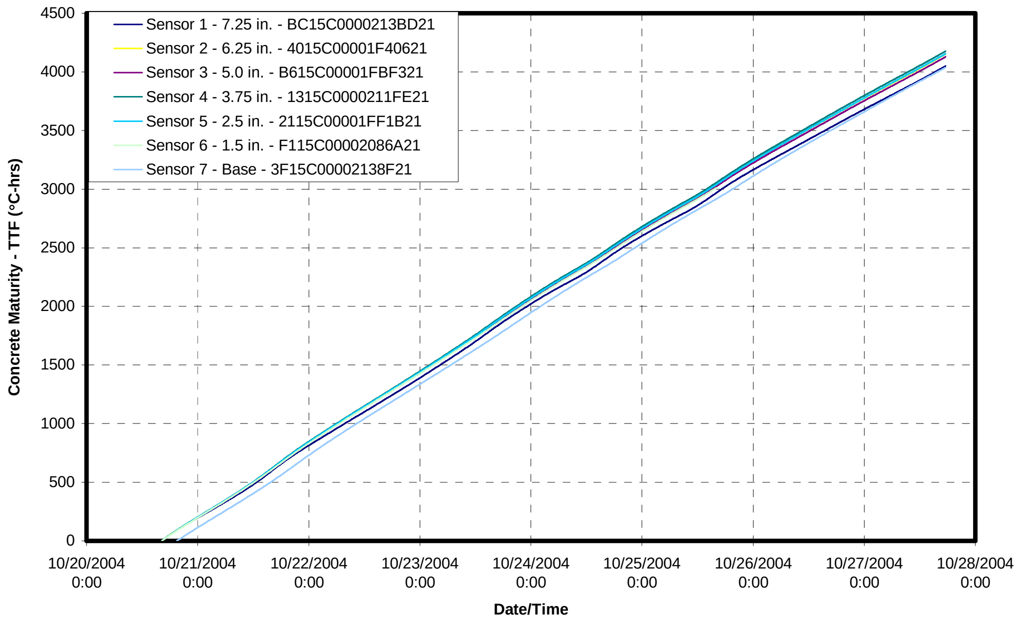

Figure C3. Slab maturity data

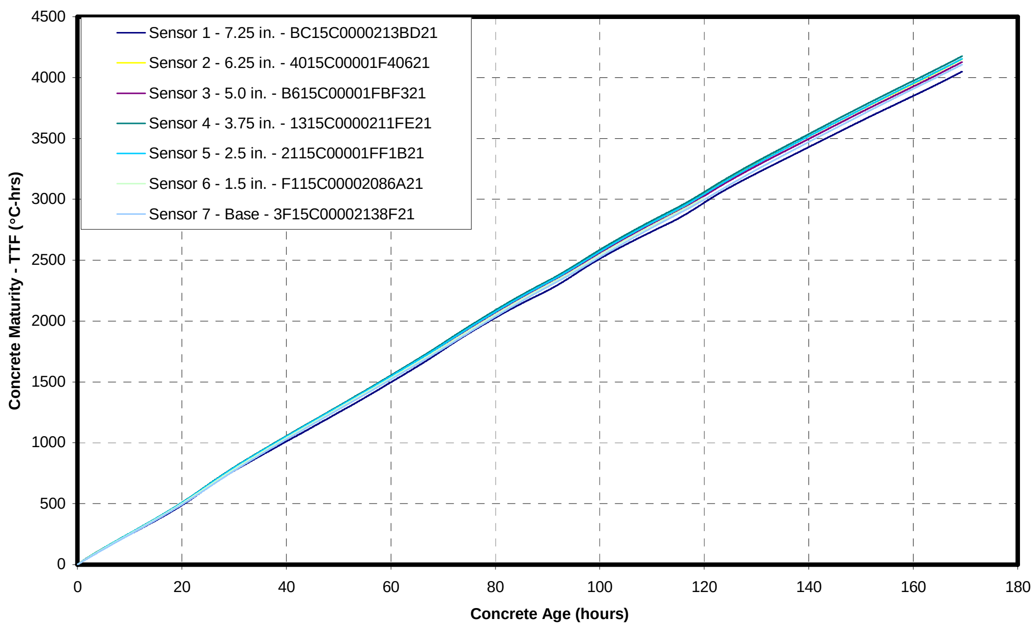

Figure C4. Slab maturity data

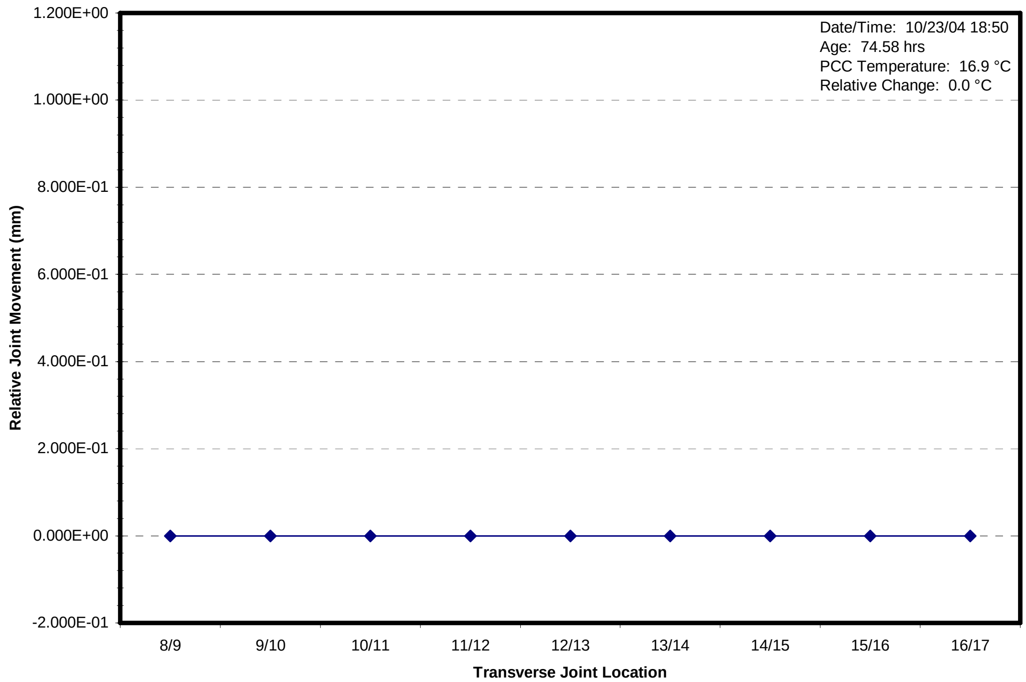

Figure C5. Transverse joint relative opening

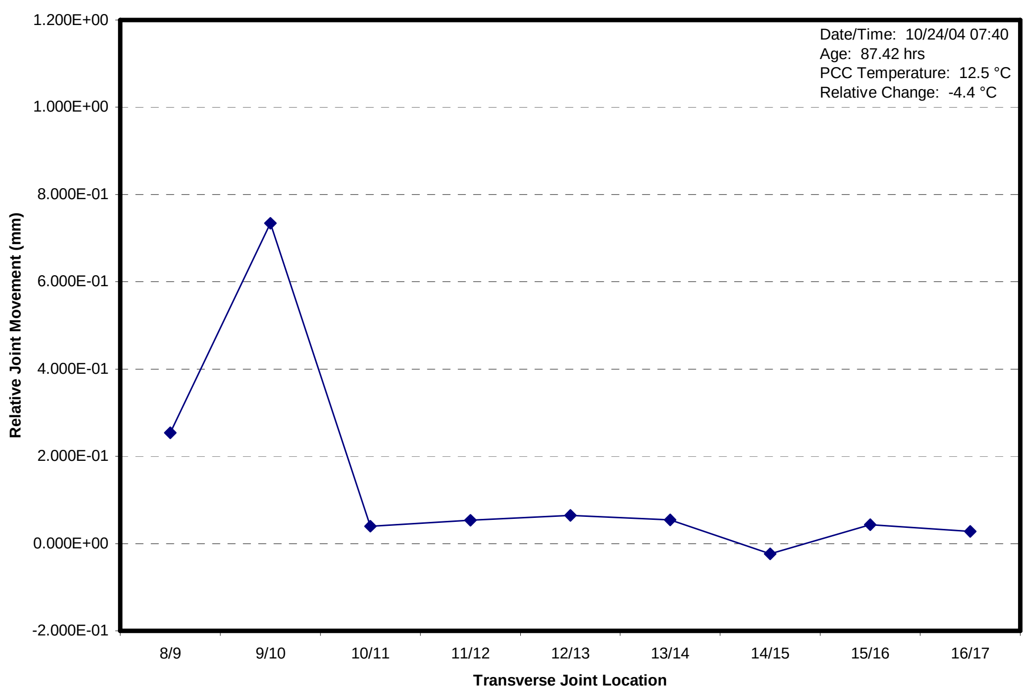

Figure C6. Transverse joint relative opening

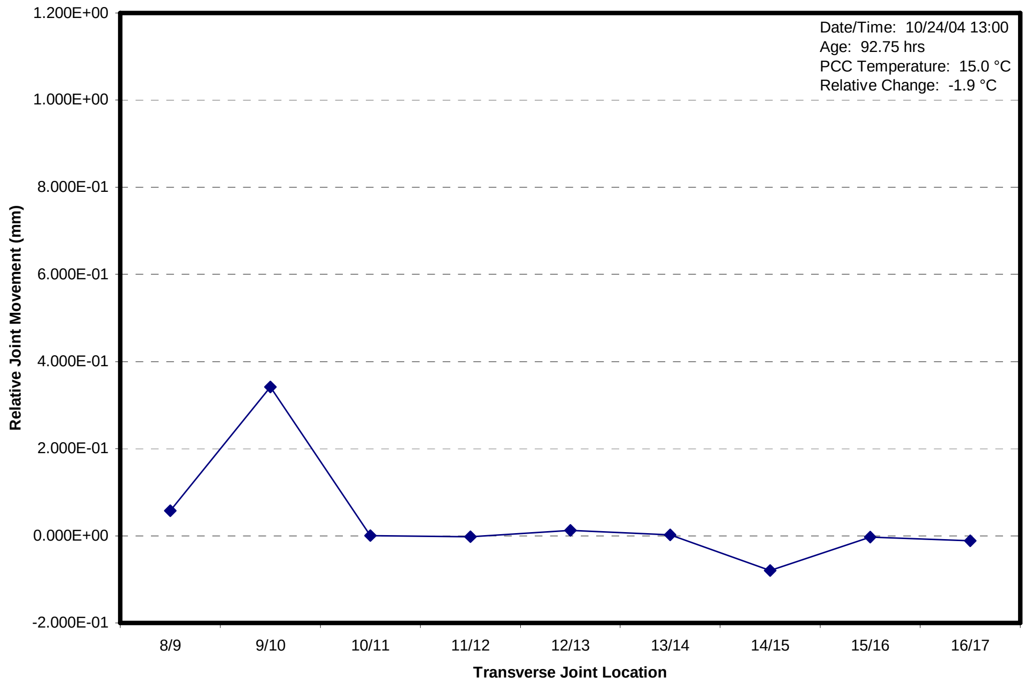

Figure C7. Transverse joint relative opening

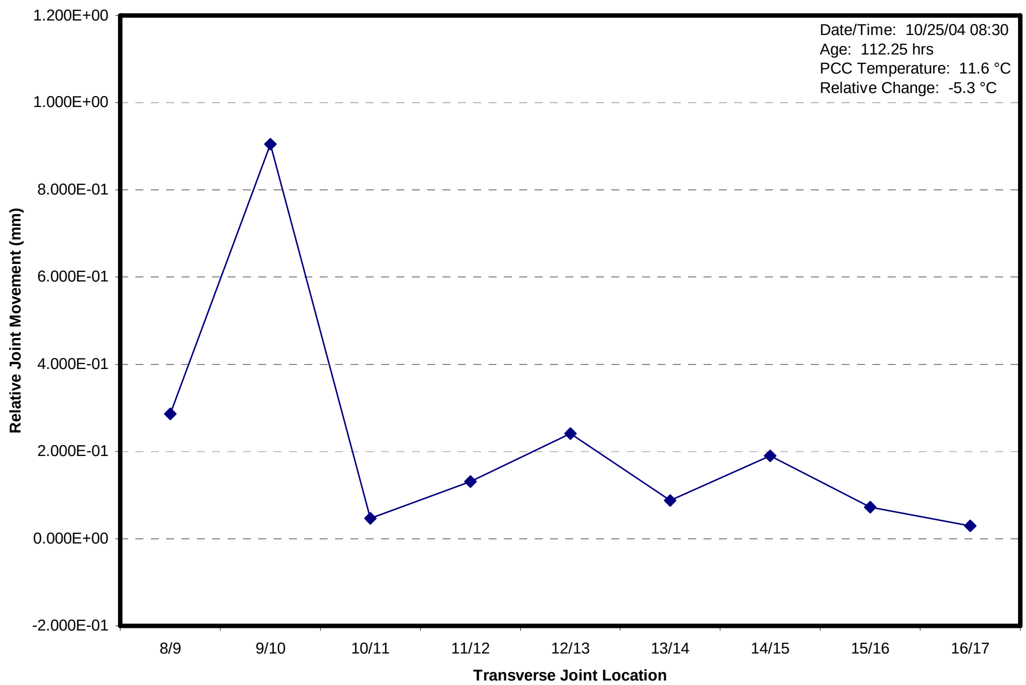

Figure C8. Transverse joint relative opening

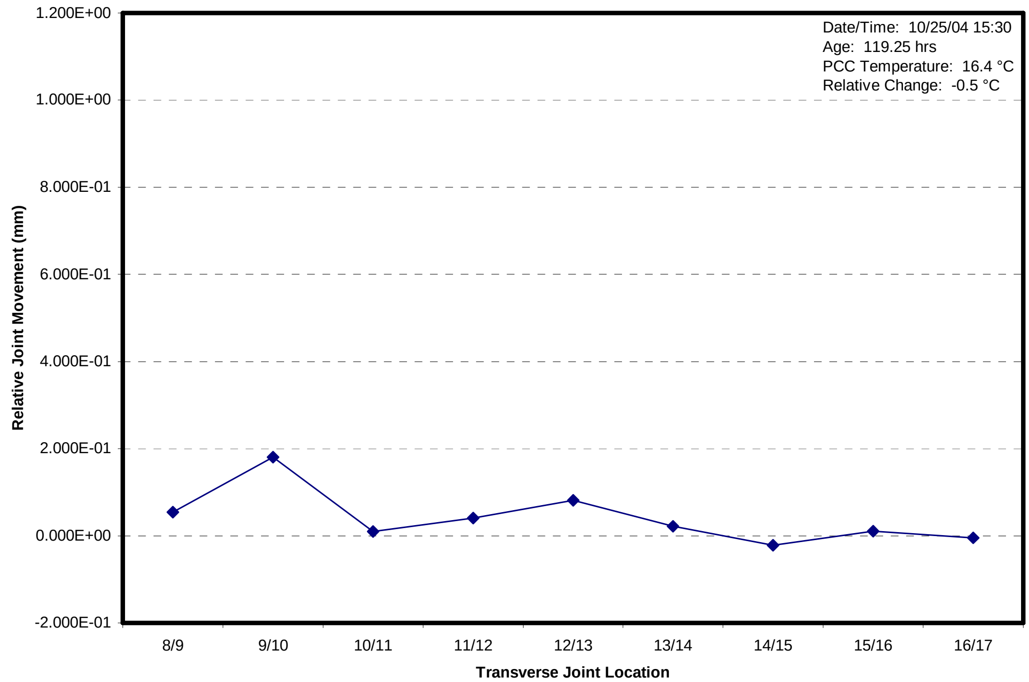

Figure C9. Transverse joint relative opening

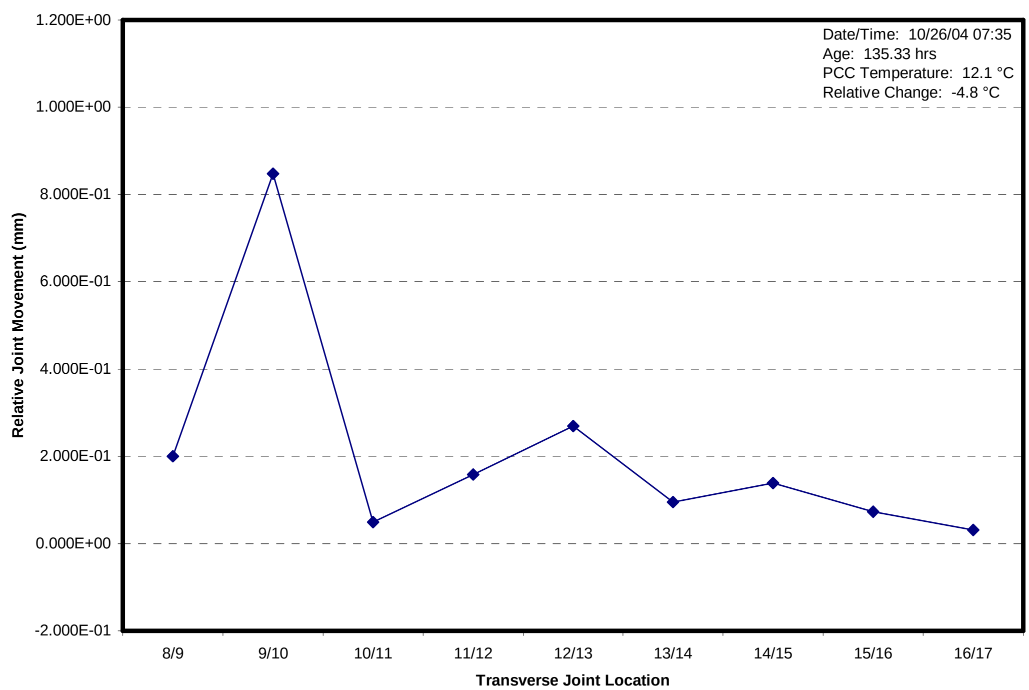

Figure C10. Transverse joint relative opening

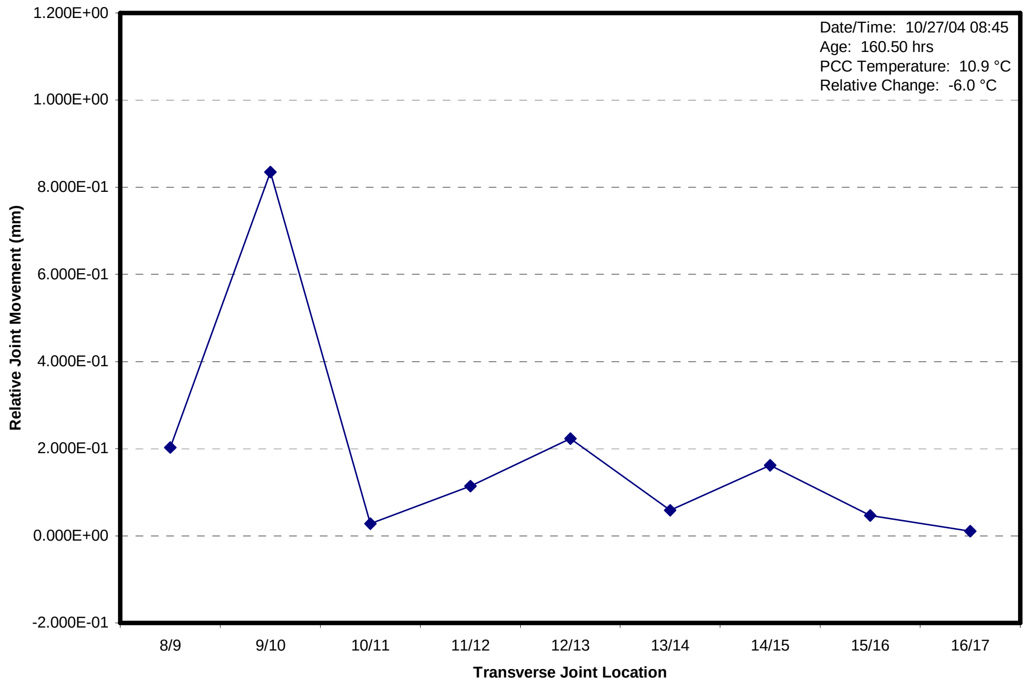

Figure C11. Transverse joint relative opening

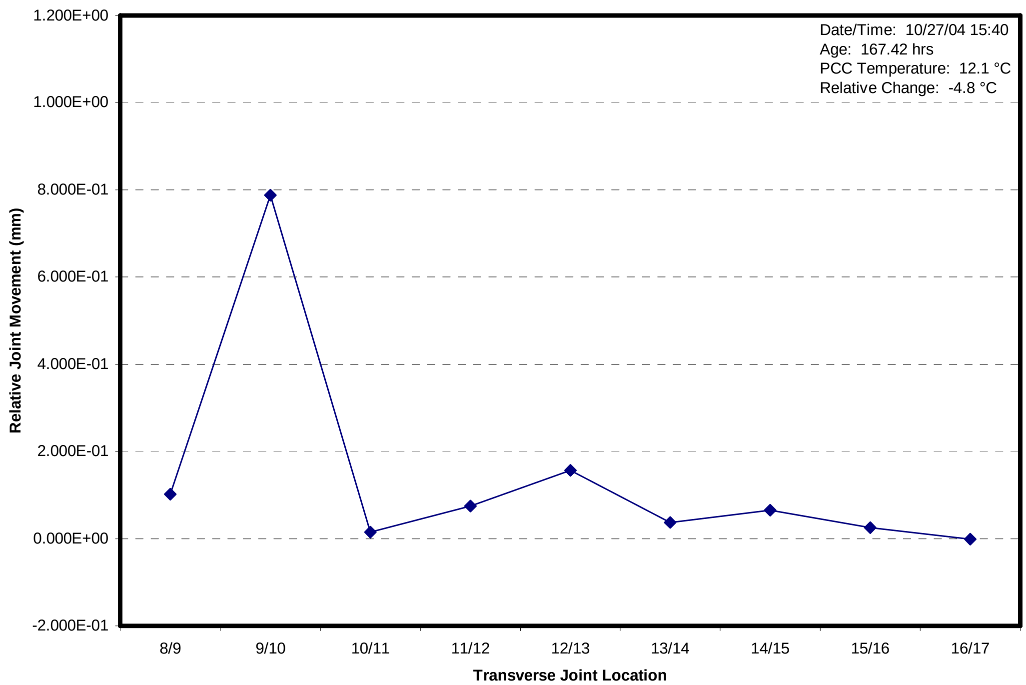

Figure C12. Transverse joint relative opening

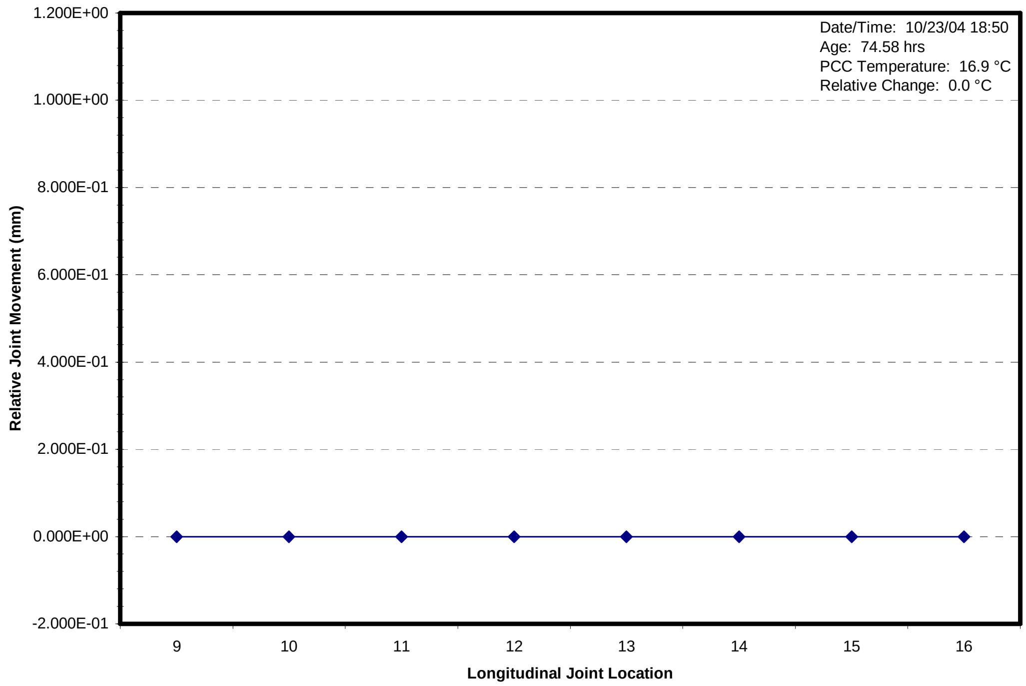

Figure C13. Longitudinal joint relative opening

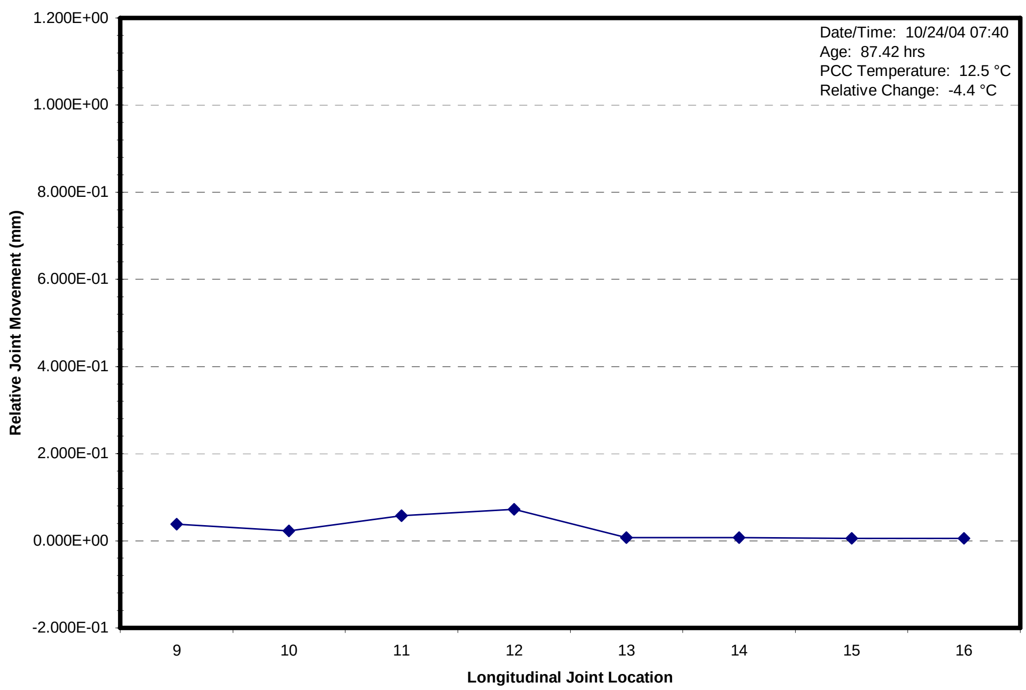

Figure C14. Longitudinal joint relative opening

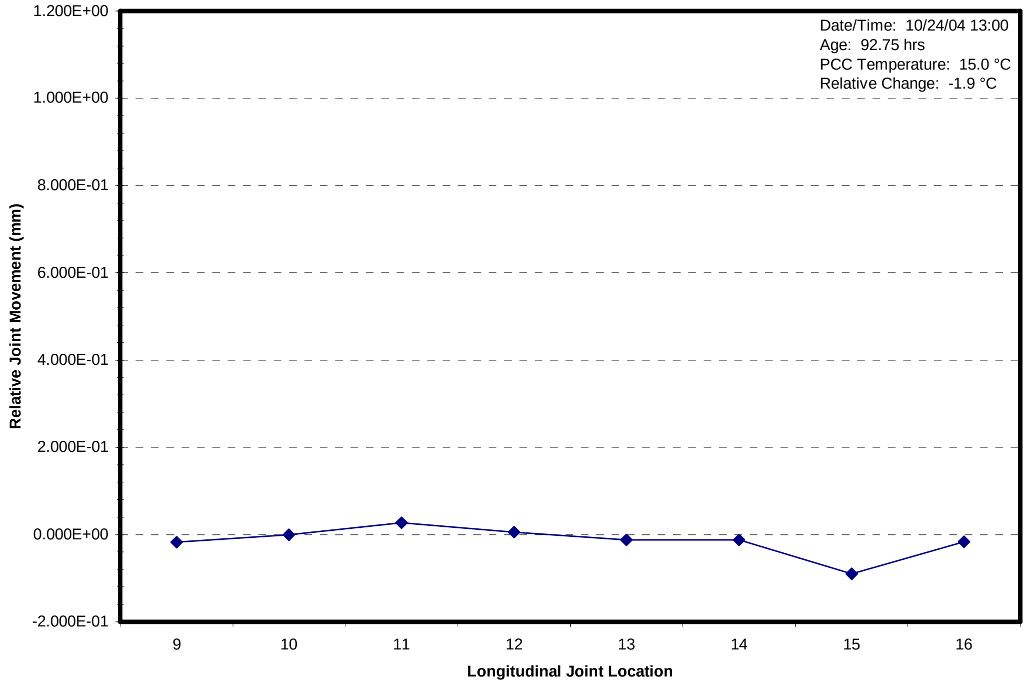

Figure C15. Longitudinal joint relative opening

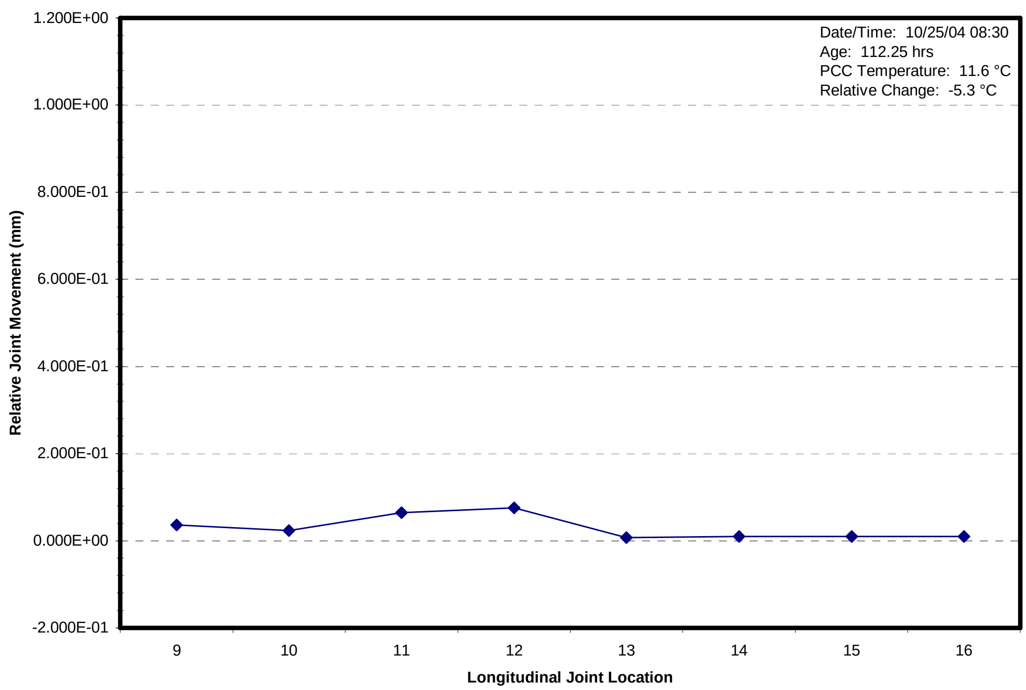

Figure C16. Longitudinal joint relative opening

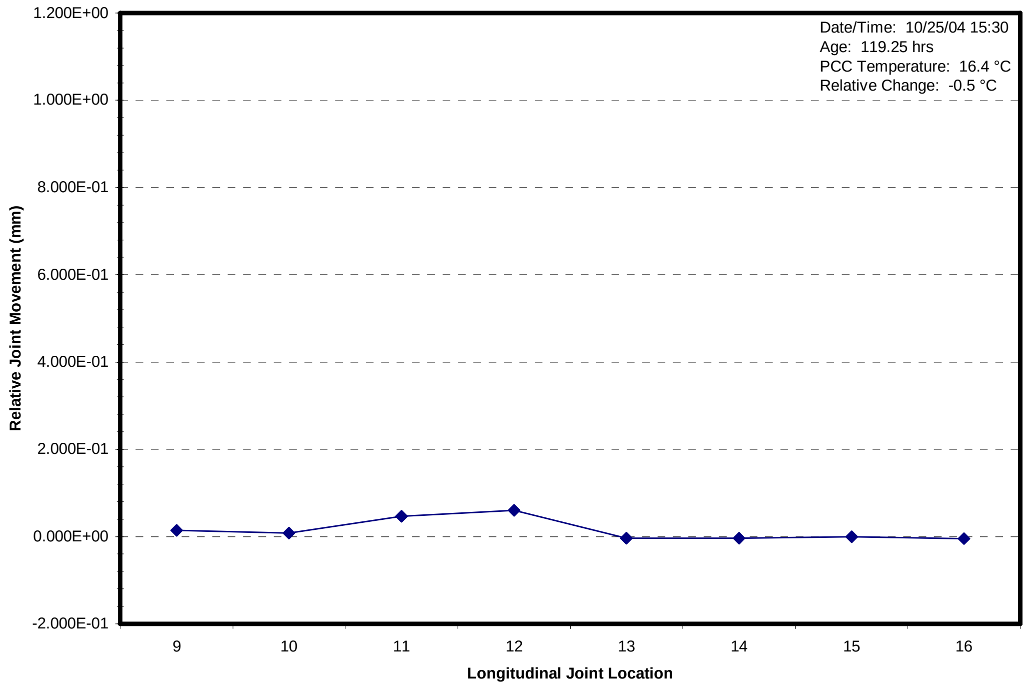

Figure C17. Longitudinal joint relative opening

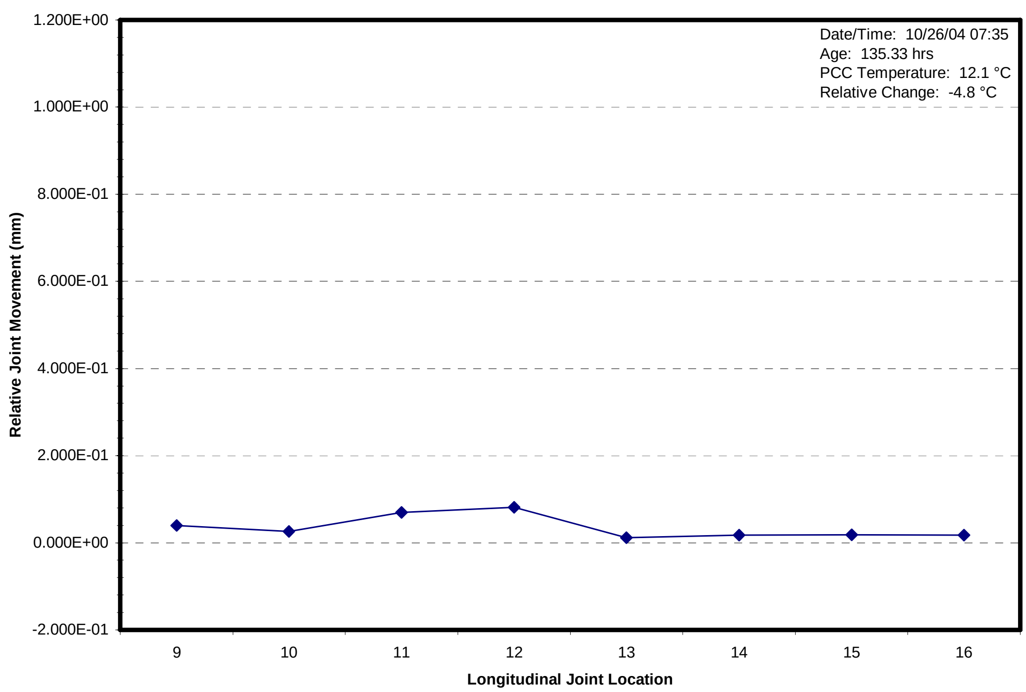

Figure C18. Longitudinal joint relative opening

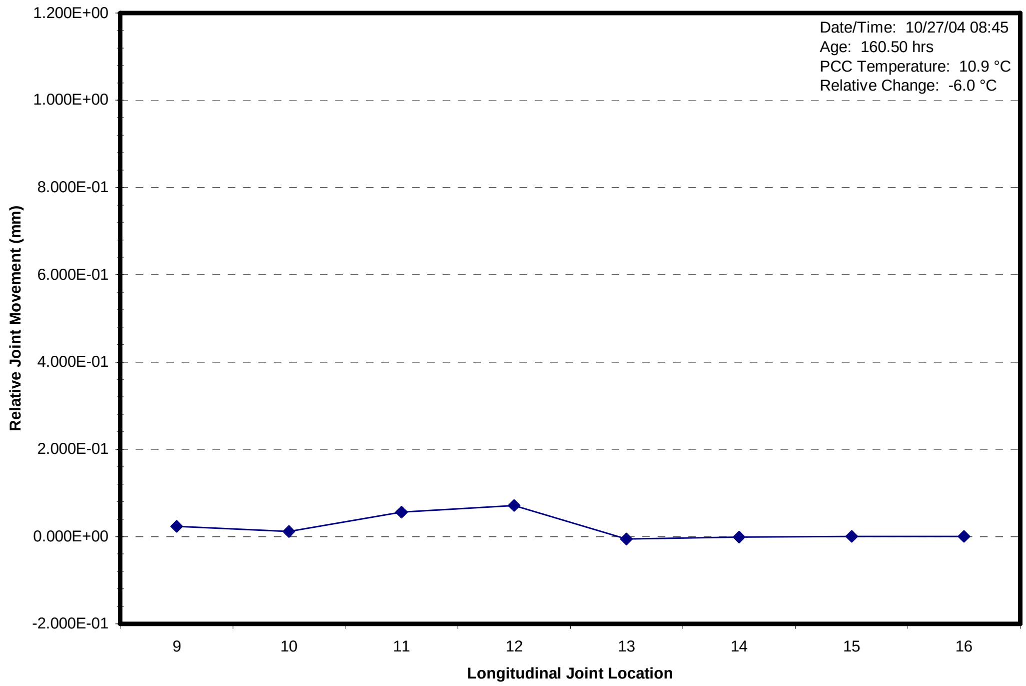

Figure C19. Longitudinal joint relative opening

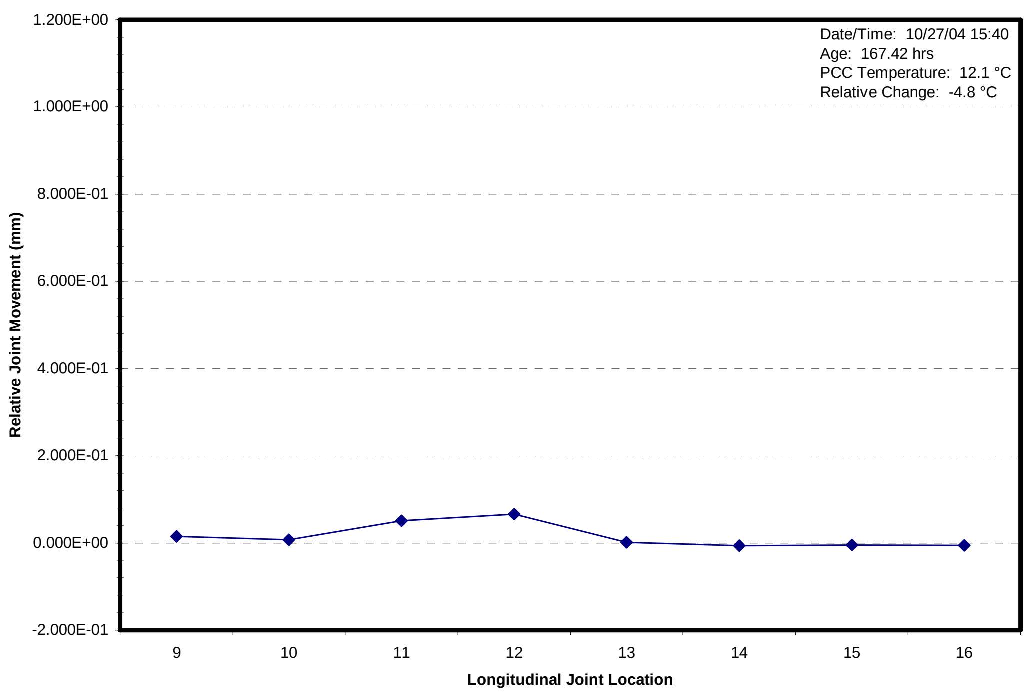

Figure C20. Longitudinal joint relative opening

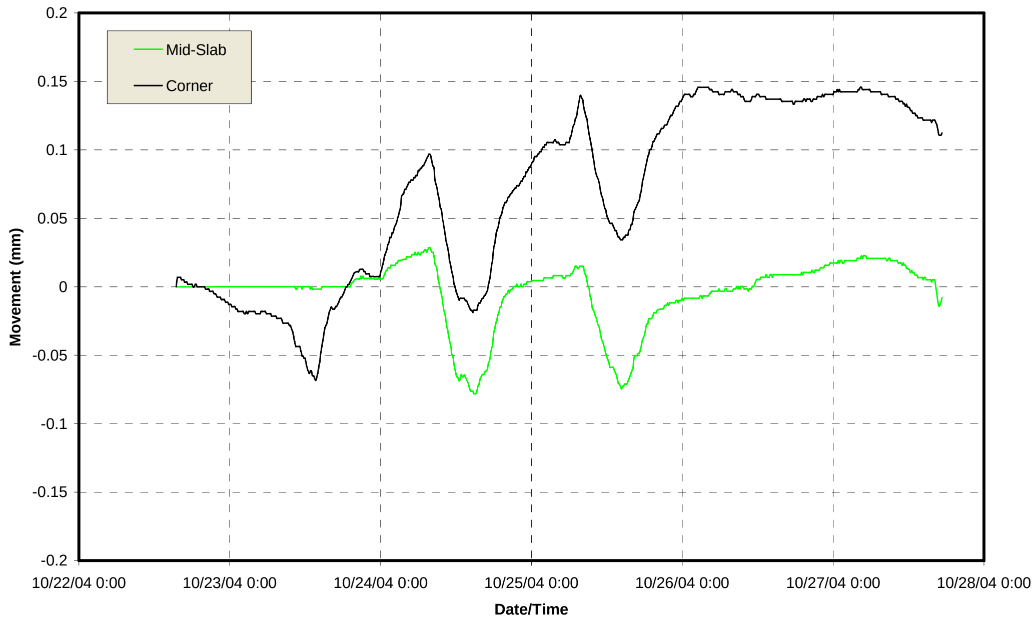

Figure C21. LVDT record

Table C1. Level A slab edge profile summary

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
2A23E	10/21/2004 16:00	23.75	20.1	15.3	99.2	211.9	2.93
2A31E	10/22/2004 8:30	40.25	14.6	10.1	101.4	190.3	3.09
2A42E	10/23/2004 9:45	65.50	16.2	18.7	99.8	164.9	3.3
2A43E	10/23/2004 15:15	71.00	17.9	13.7	89.5	165.2	3.29
2A51E	10/24/2004 7:30	87.25	12.5	10.3	92.5	158.8	3.35
2A53E	10/24/2004 12:00	91.75	14.0	14.2	90.4	156.2	3.37
2A61E	10/25/2004 8:20	112.08	11.6	8.4	85.1	149.1	3.43
2A63E	10/25/2004 15:15	119.00	16.3	17.2	88.2	144.9	3.47
2A71E	10/26/2004 6:30	134.25	12.1	9.6	88.1	162.8	3.31
2A81E	10/27/2004 8:30	160.25	10.9	9.6	88.5	145.8	3.46
2A83E	10/27/2004 15:00	166.75	12.1	11.8	91.3	148.3	3.44

Table C2. Level A mid-slab profile summary

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
2A31 M	10/22/2004 8:30	40.25	14.6	10.1	73.4	122.1	3.67
2A42 M	10/23/2004 9:45	65.50	16.2	18.7	84.1	269.4	2.53
2A43 M	10/23/2004 15:15	71.00	17.9	13.7	71.9	112.6	3.76
2A51 M	10/24/2004 7:30	87.25	12.5	4.8	67.4	114.8	3.74
2A53 M	10/24/2004 12:00	91.75	14.0	14.2	71.7	121.4	3.68
2A61 M	10/25/2004 8:20	112.08	11.6	8.4	69.9	117.6	3.72
2A63 M	10/25/2004 15:15	119.00	16.3	17.2	74.7	119.7	3.7
2A71 M	10/26/2004 6:30	134.25	12.1	9.6	68.9	124.9	3.65
2A81 M	10/27/2004 8:30	160.25	10.9	9.6	68.1	122.9	3.67
2A83 M	10/27/2004 15:00	166.75	12.1	11.8	72.6	118.6	3.71

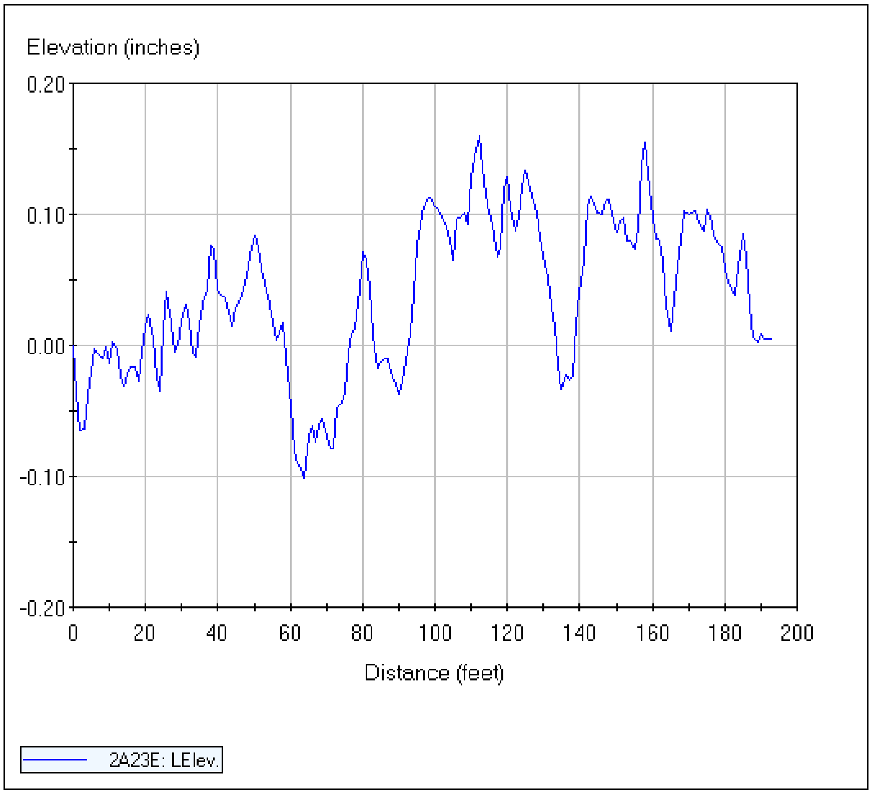

Figure C22. Level A profile, edge only, Oct. 21, 2004, 16:00

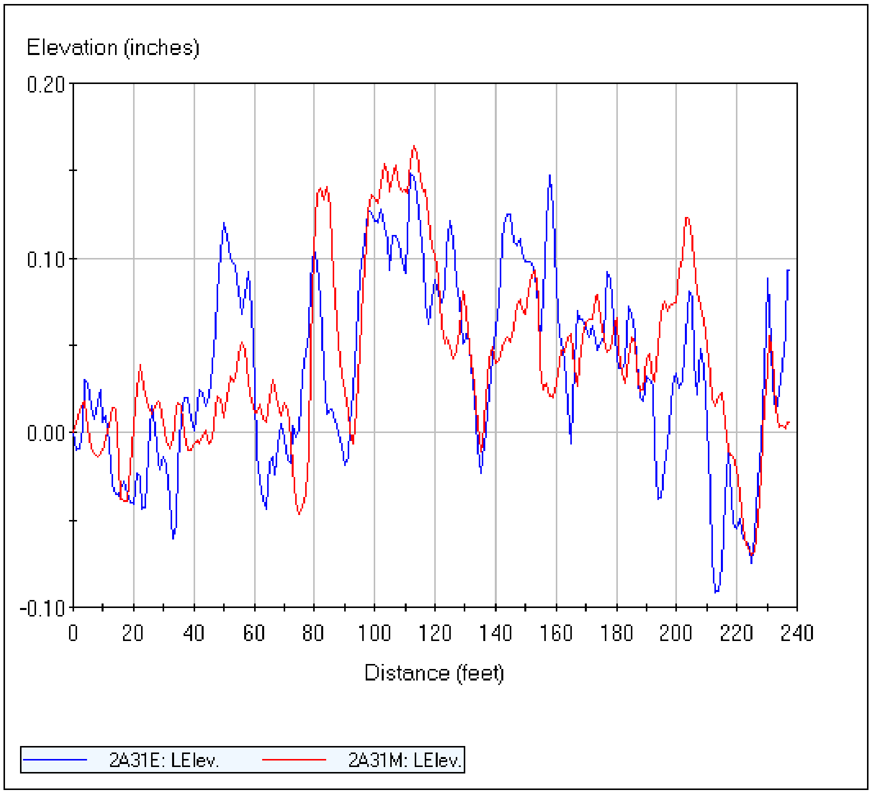

Figure C23. Level A profile, Oct. 22, 2004, 08:30

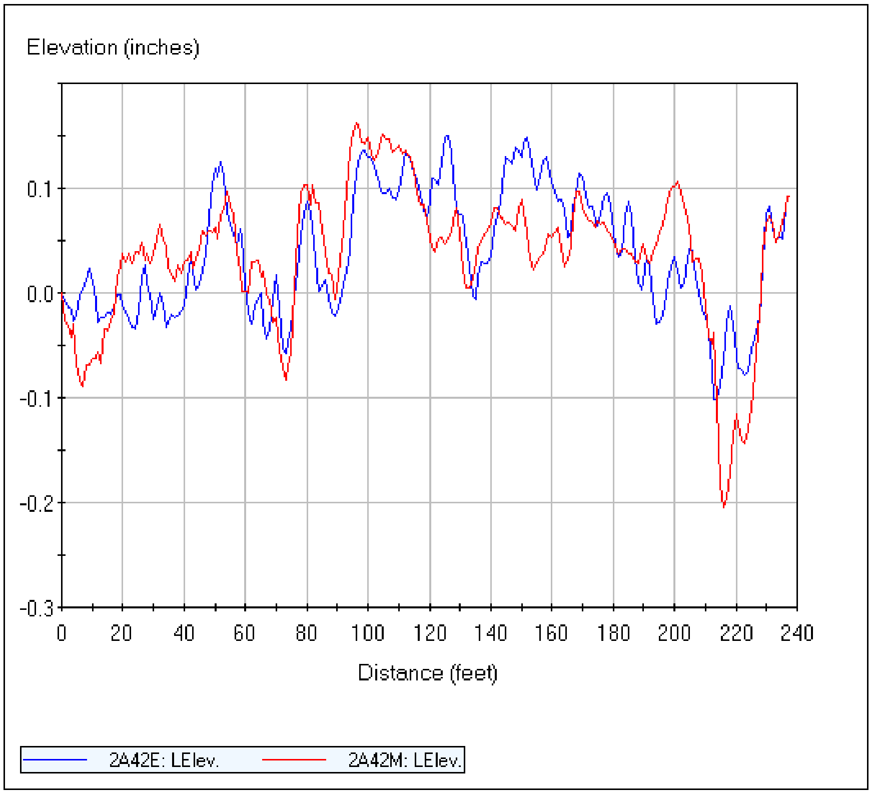

Figure C24. Level A profile, Oct. 23, 2004, 09:45

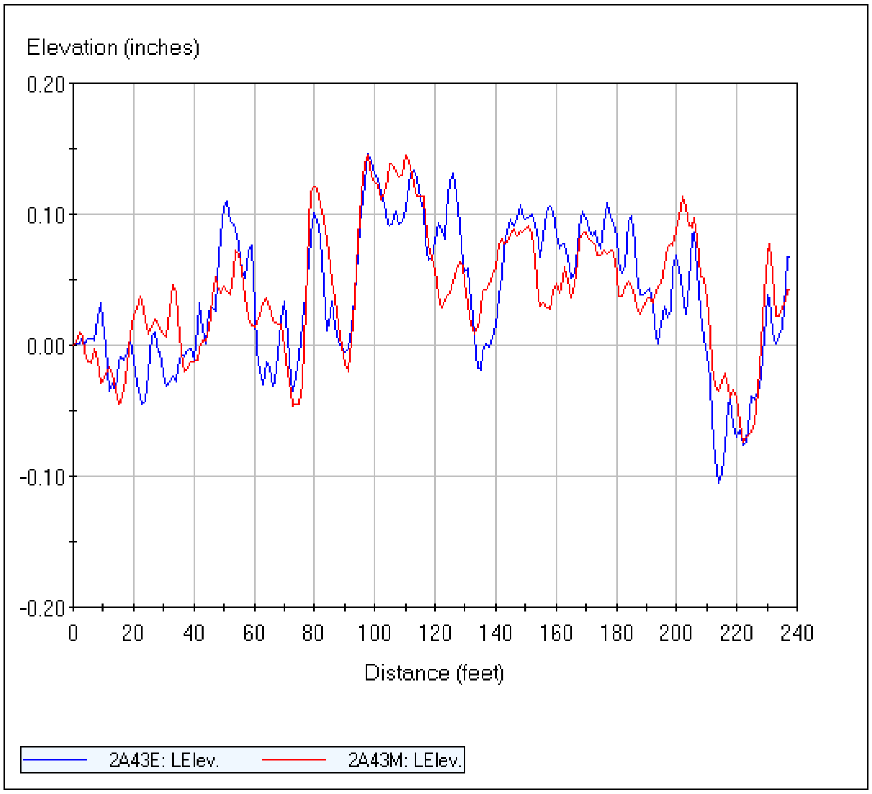

Figure C25. Level A profile, Oct. 23, 2004, 15:15

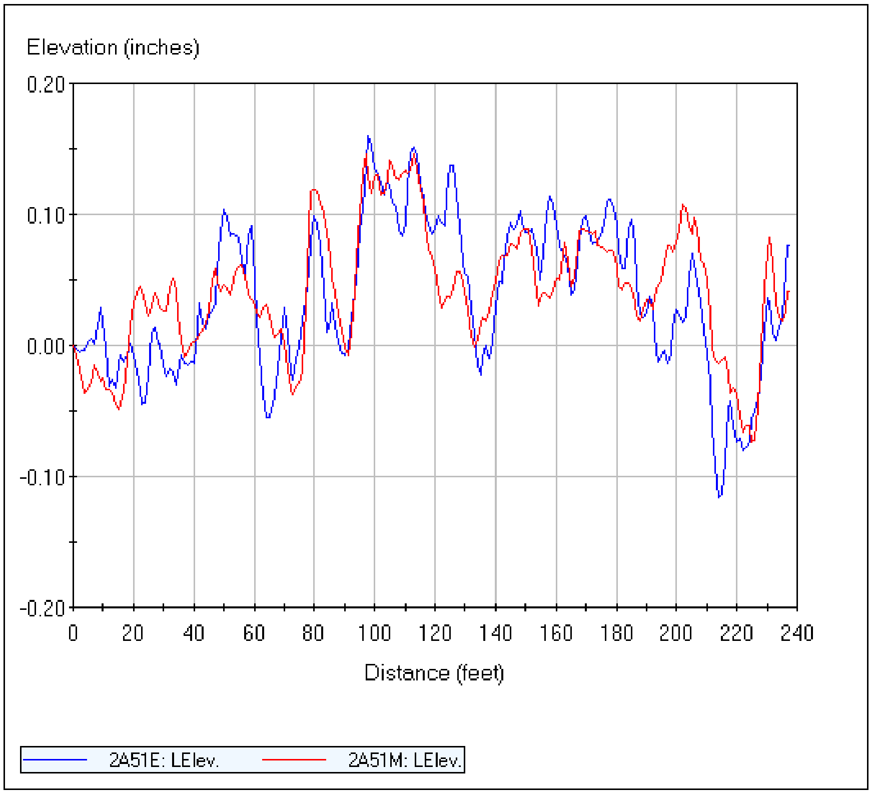

Figure C26. Level A profile, Oct. 24, 2004, 07:30

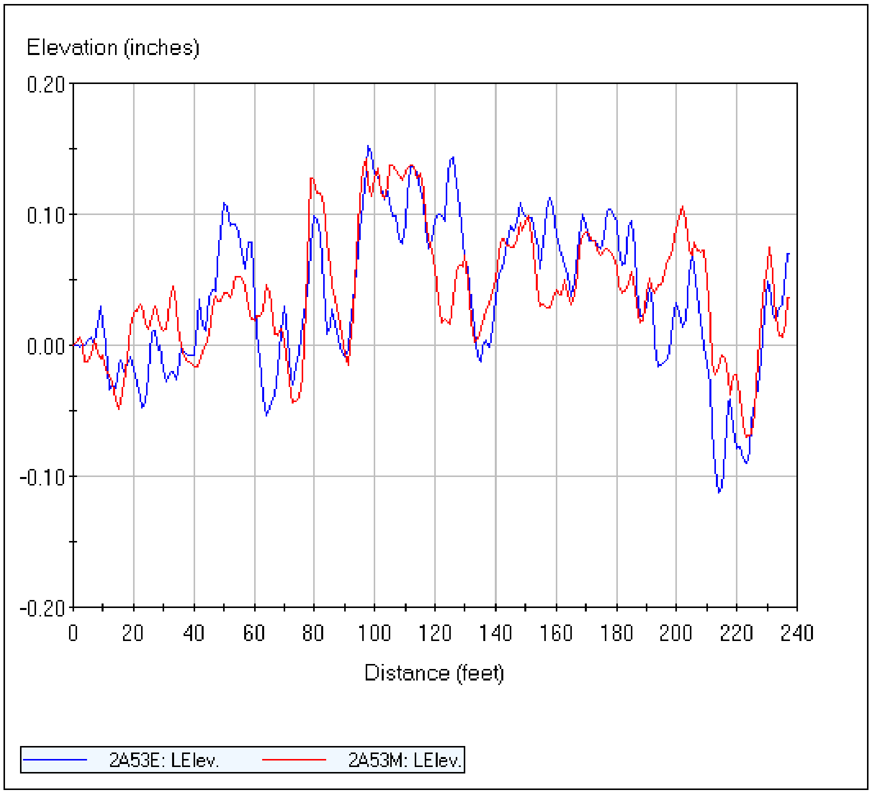

Figure C27. Level A profile, Oct. 24, 2004, 12:00

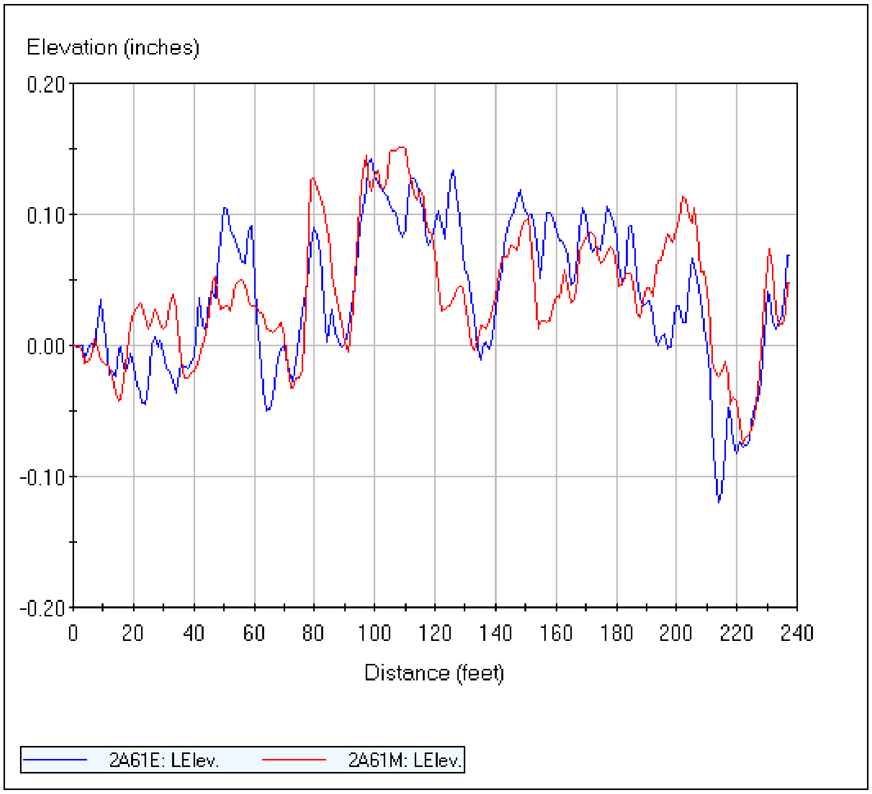

Figure C28. Level A profile, Oct. 25, 2004, 08:20

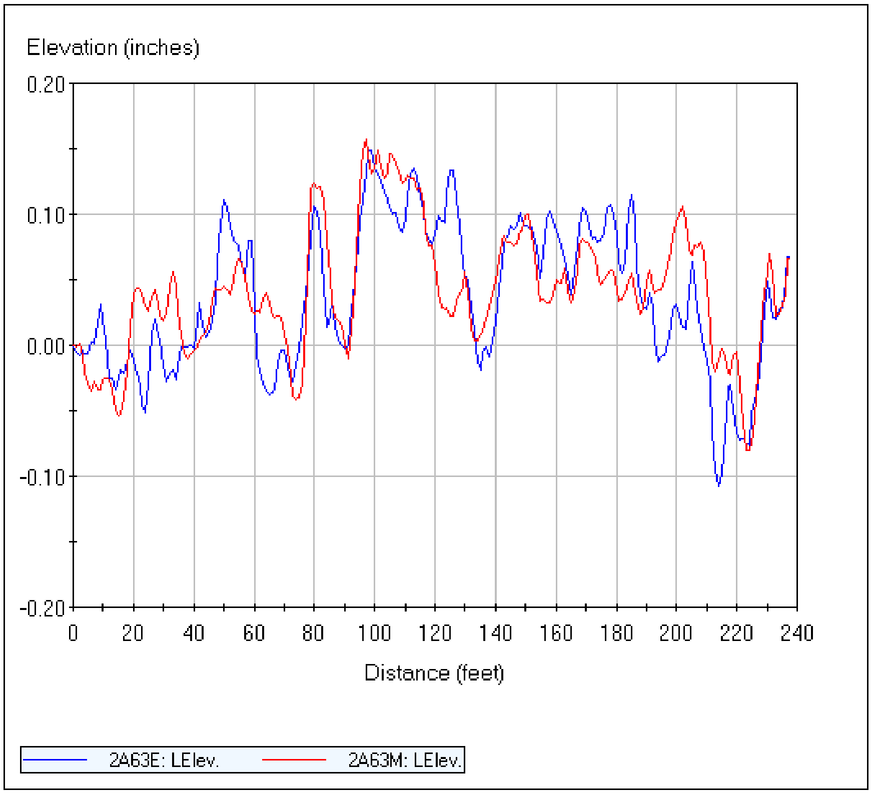

Figure C29. Level A profile, Oct. 25, 2004, 15:15

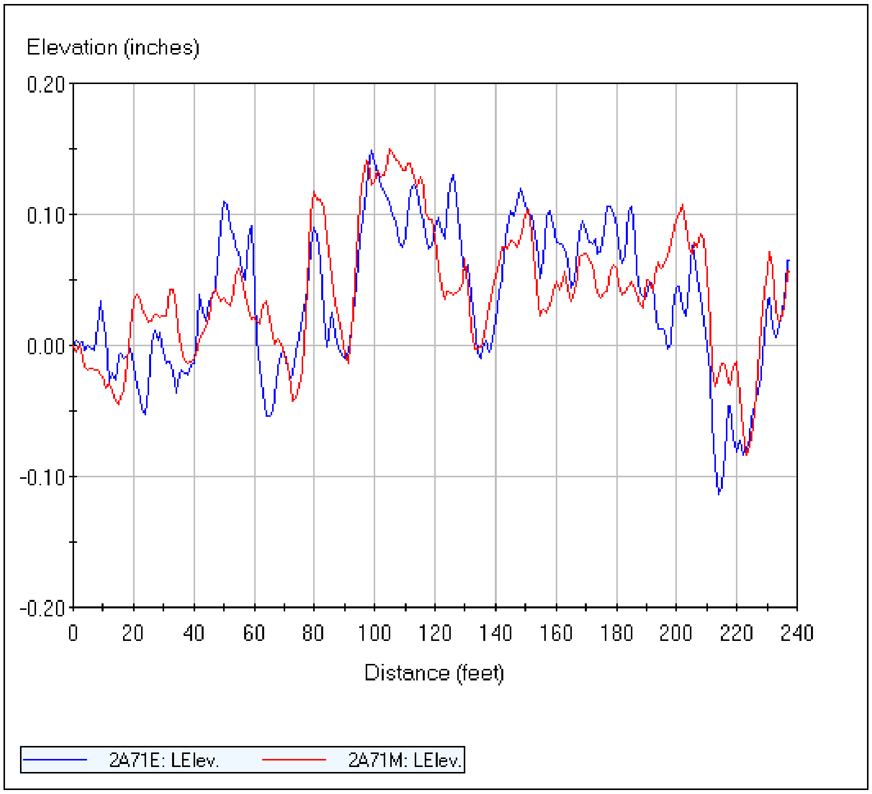

Figure C30. Level A profile, Oct. 26, 2004, 06:30

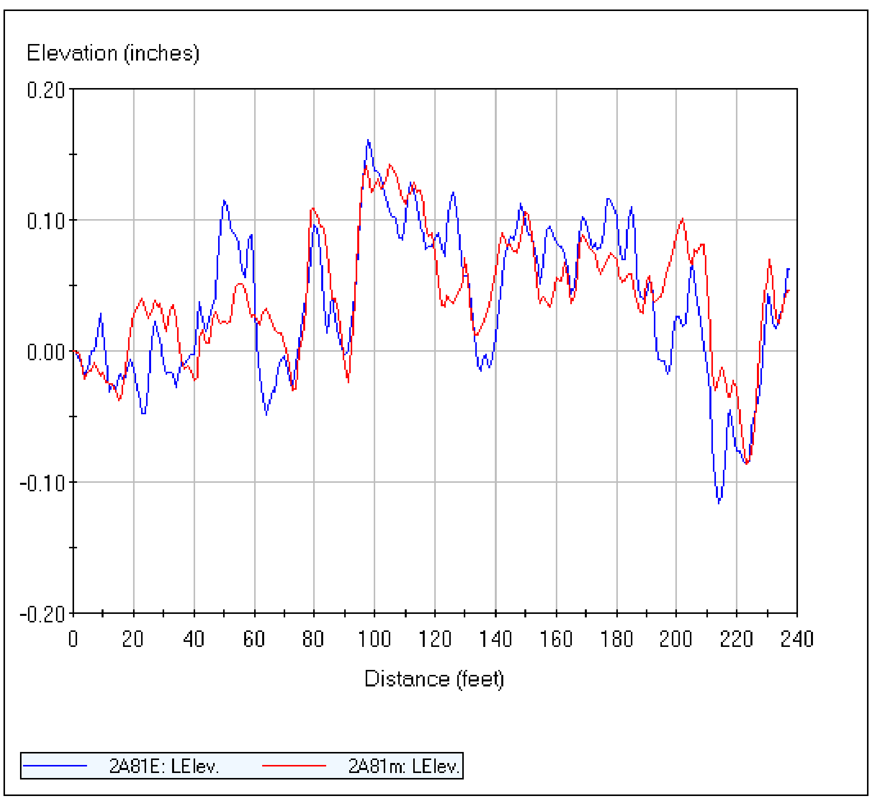

Figure C31. Level A profile, Oct. 27, 2004, 08:30

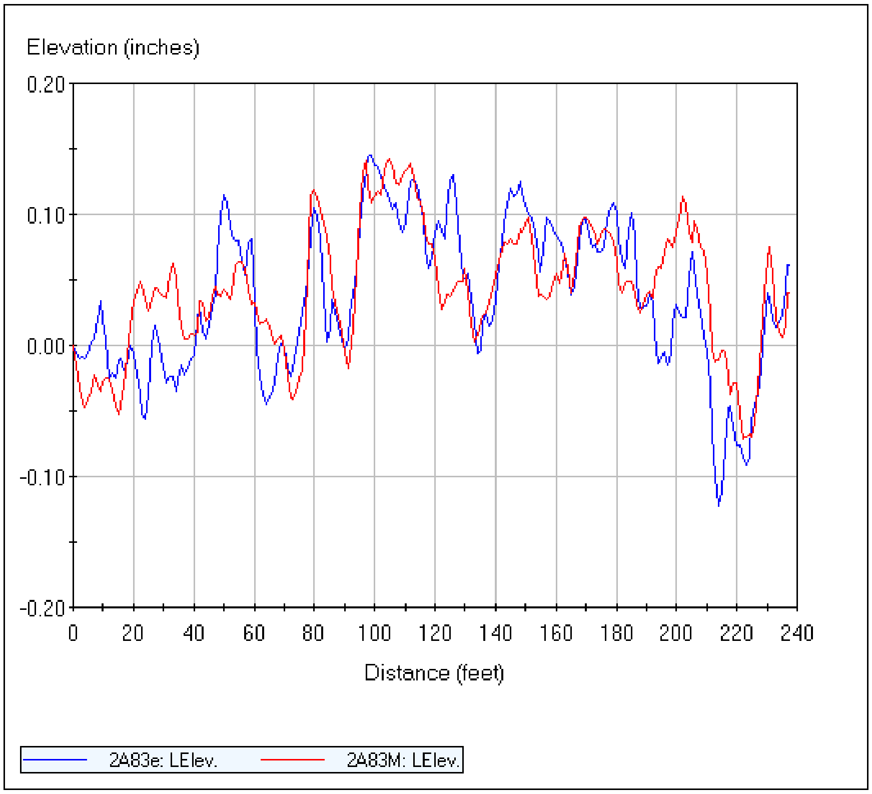

Figure C32. Level A profile, Oct. 27, 2004, 15:00

Table C3. Level B profile summary (1.5 ft from free edge)

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
2B143A	10/23/2004 16:15	72.00	17.7	13.3	61.2	159.8	3.34
2B153A	10/24/2004 13:00	92.75	15.0	16.1	60.3	135.1	3.55
2B163A	10/25/2004 16:15	120.00	16.9	16.9	60.1	121.9	3.68
2B183A	10/27/2004 16:00	167.75	12.1	11.8	55.6	127.3	3.63

Table C4. Level B profile summary (3 ft from free edge)

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
2B143B	10/23/2004 16:15	72.00	17.7	13.3	60.4	145.5	3.46
2B153B	10/24/2004 13:00	92.75	15.0	16.1	72.9	137.4	3.53
2B163B	10/25/2004 16:15	120.00	16.9	16.9	58.4	116.9	3.72
2B183B	10/27/2004 16:00	167.75	12.1	11.8	59.2	106.2	3.82

Table C5. Level B profile summary (3 ft from longitudinal joint)

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
2B243A	10/23/2004 16:15	72.00	17.7	13.3	47.7	118.1	3.71
2B253A	10/24/2004 13:00	92.75	15.0	16.1	48.8	105	3.84
2B263A	10/25/2004 16:15	120.00	16.9	16.9	47.4	109.5	3.79
2B283A	10/27/2004 16:00	167.75	12.1	11.8	44.2	107.2	3.81

Table C6. Level B profile summary (1 ft from longitudinal joint)

File Name	Date/Time	Age (hrs)	Avg. Pavement Temperature (°C)	Ambient Temperature (°C)	IRI (in/mi)	PTRN (in/mi)	RN
2B243B	10/23/2004 16:15	72.00	17.7	13.3	70	148.7	3.43
2B253B	10/24/2004 13:00	92.75	15.0	16.1	67.4	138.1	3.53
2B263B	10/25/2004 16:15	120.00	16.9	16.9	56.8	109.3	3.79
2B283B	10/27/2004 16:00	167.75	12.1	11.8	54.7	84.8	4.04

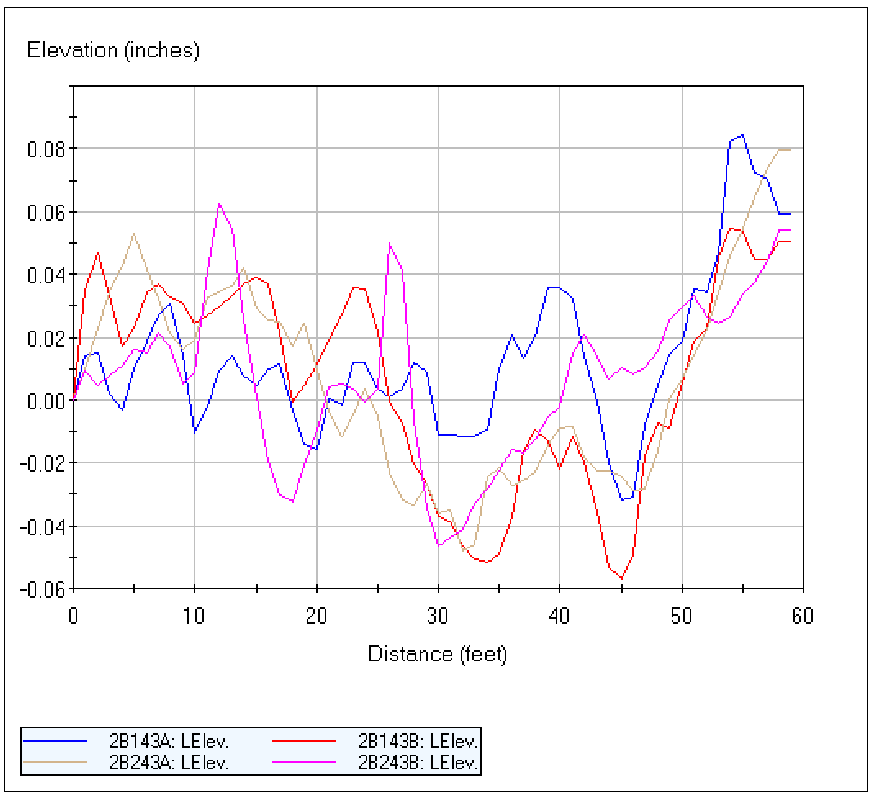

Figure C33. Level B profile, Oct. 23, 2004, 16:15

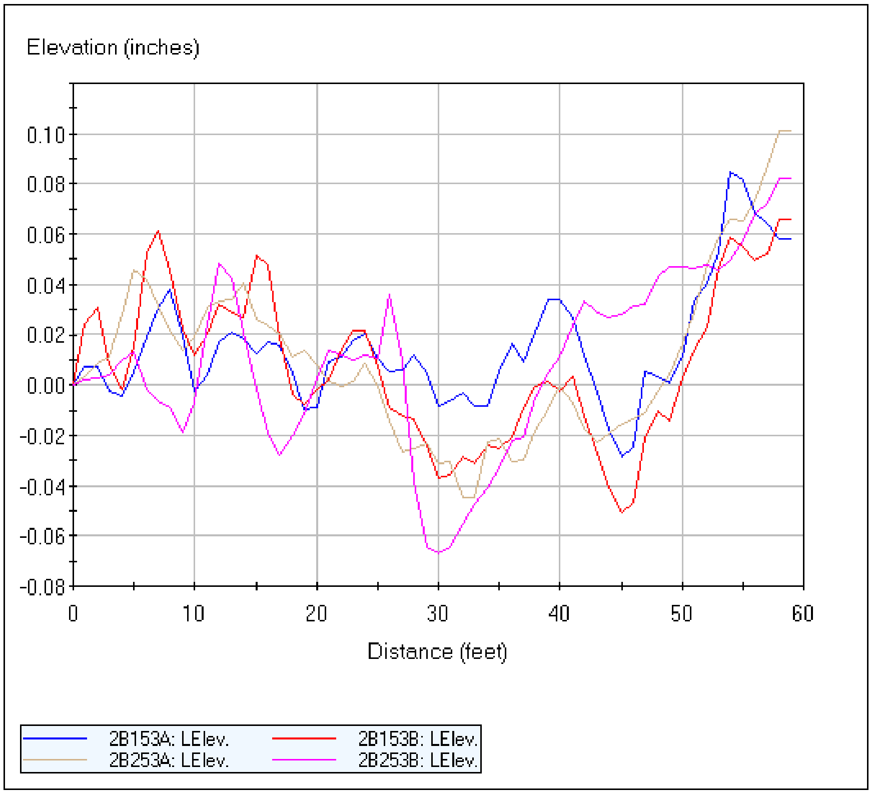

Figure C34. Level B profile, Oct. 24, 2004, 13:00

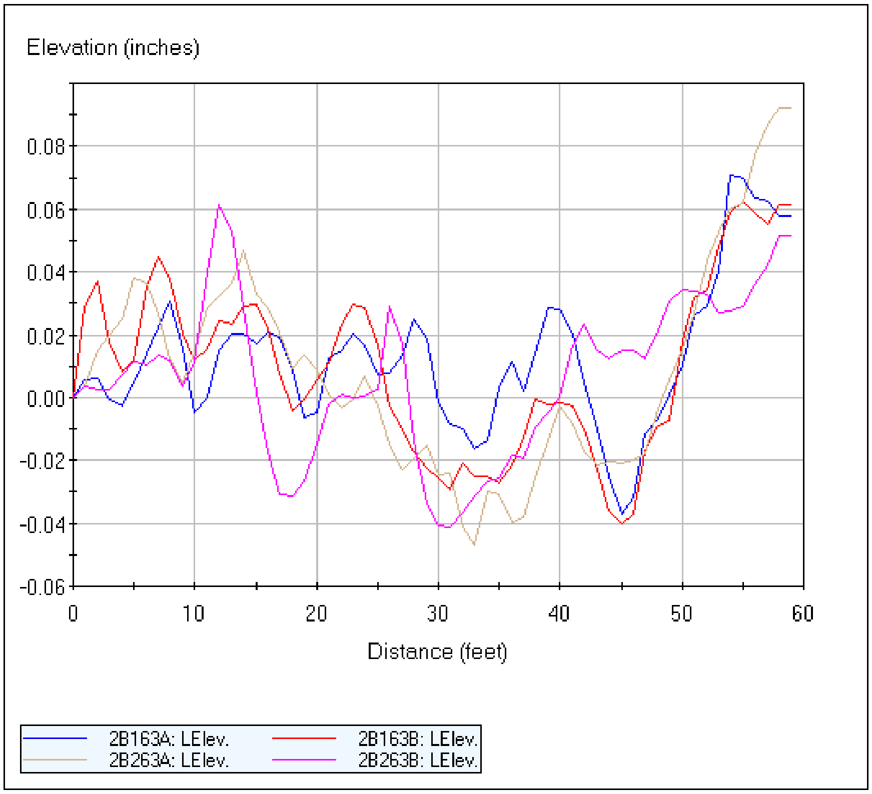

Figure C35. Level B profile, Oct. 25, 2004, 16:15

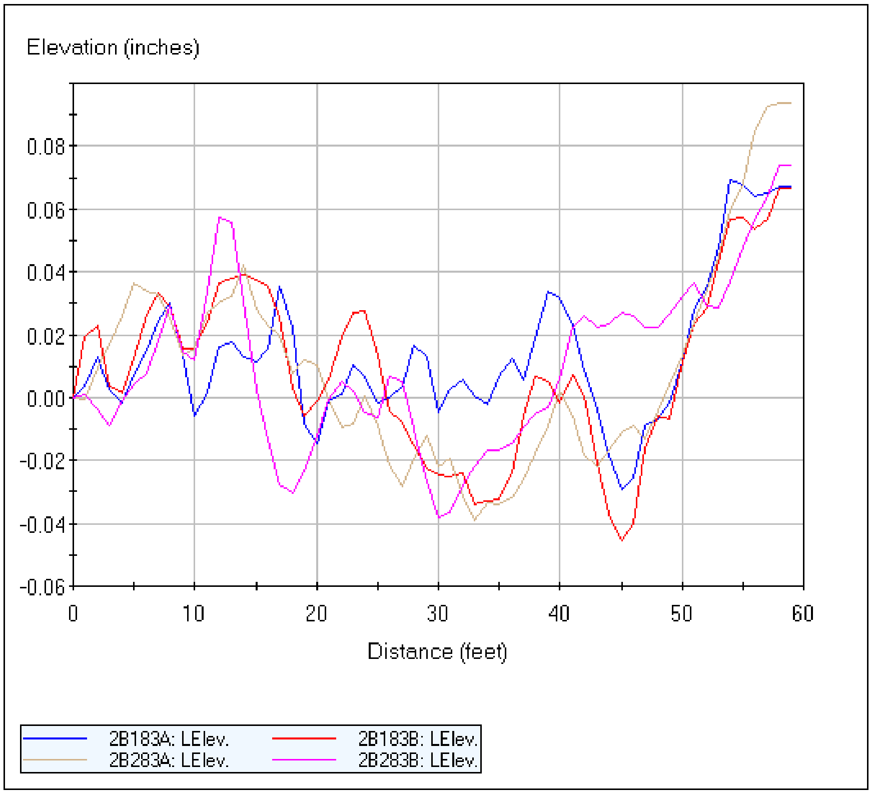

Figure C36. Level B profile, Oct. 27, 2004, 16:00

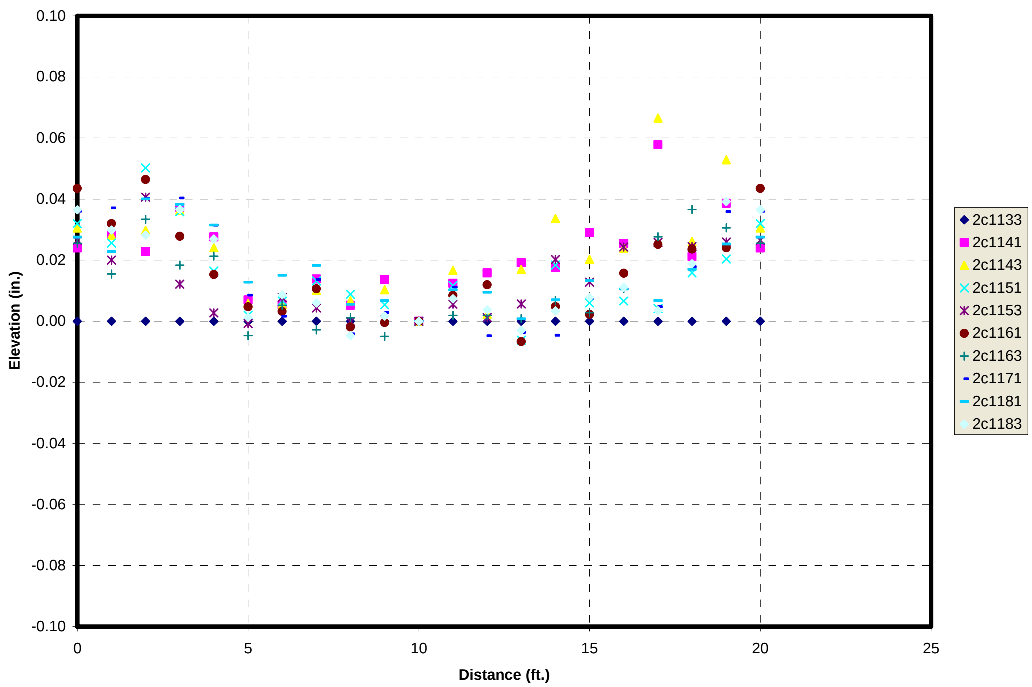

Figure C37. Level C profiles path 1, slab 11

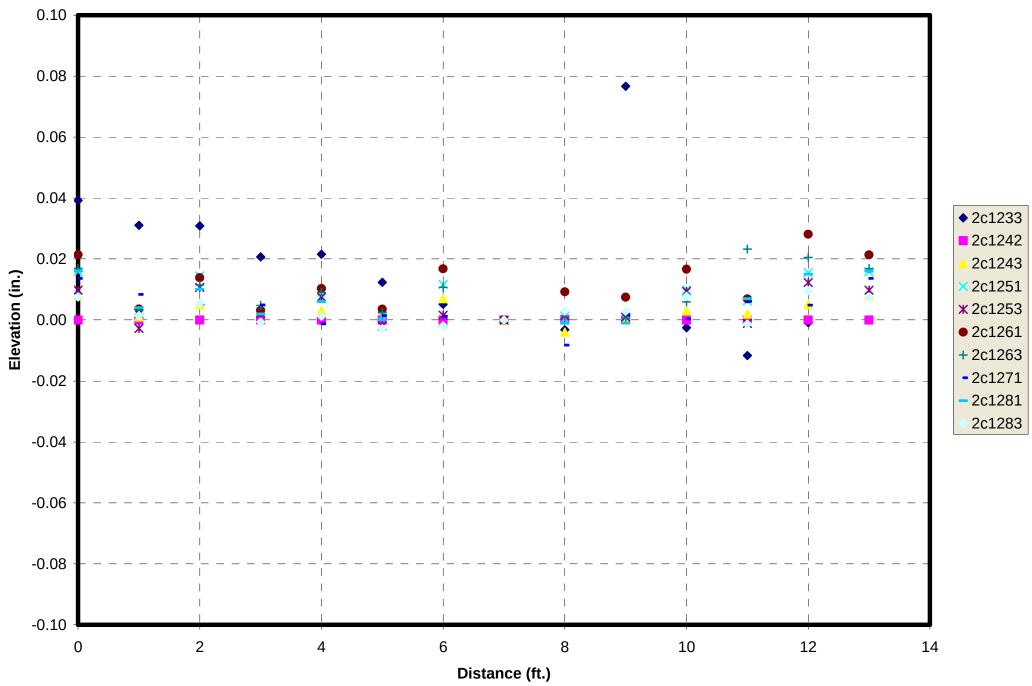

Figure C38. Level C profiles path 2, slab 11

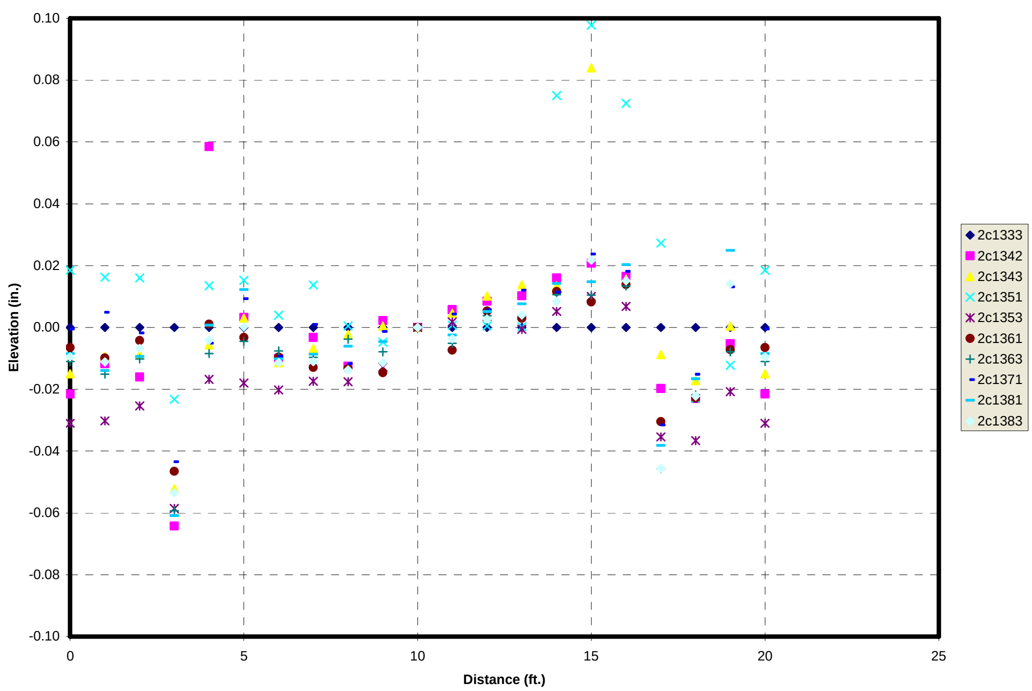

Figure C39. Level C profiles path 3, slab 11

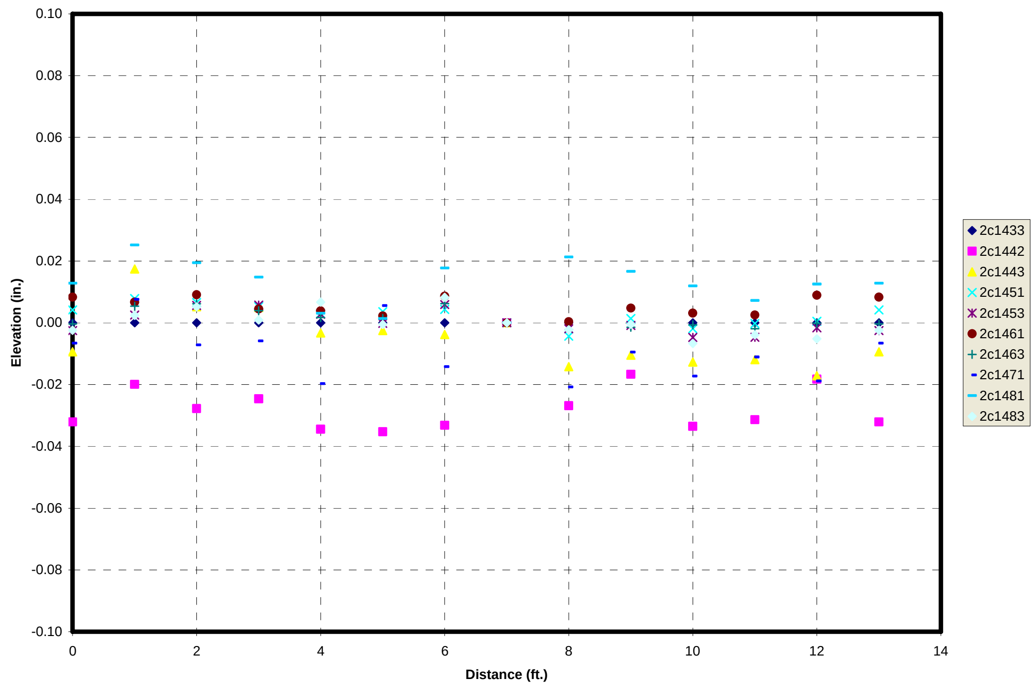

Figure C40. Level C profiles path 4, slab 11

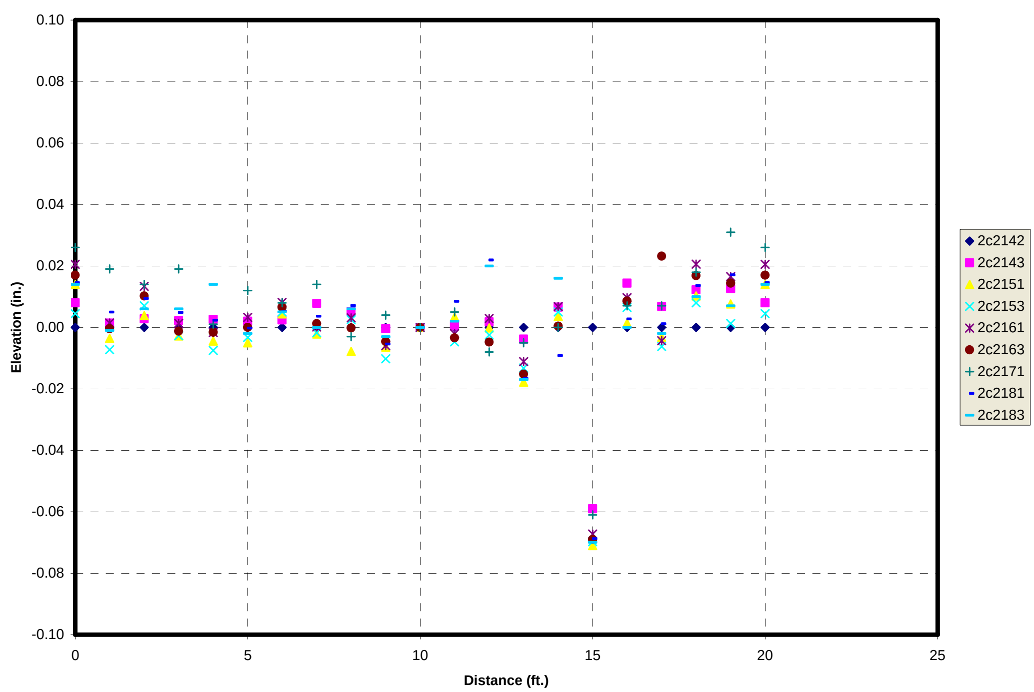

Figure C41. Level C profiles path 1, slab 12

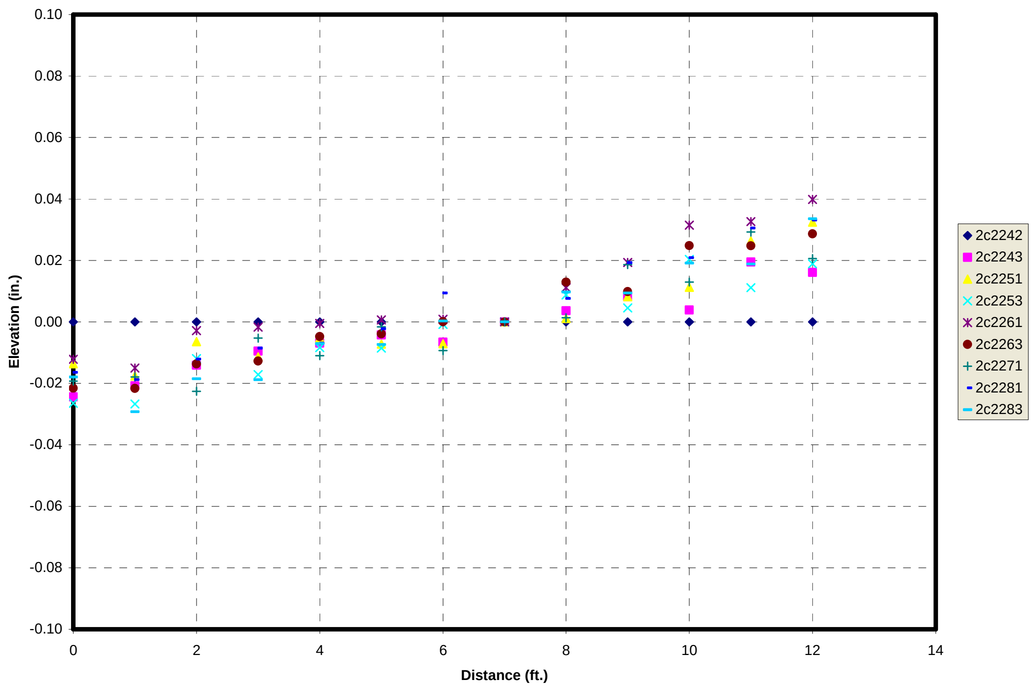

Figure C42. Level C profiles path 2, slab 12

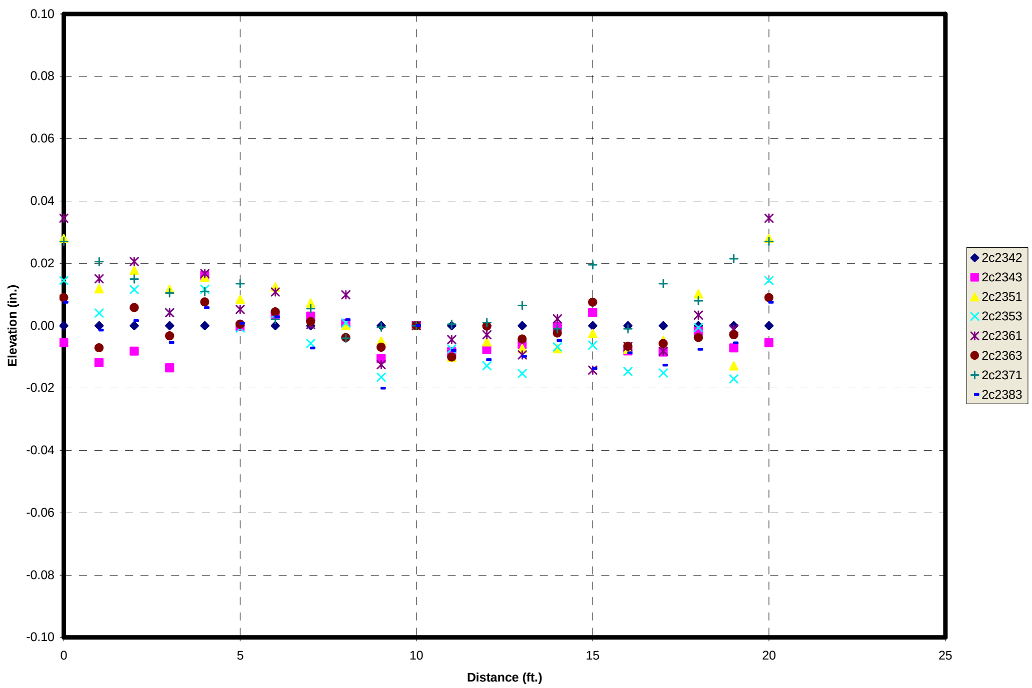

Figure C43. Level C profiles path 3, slab 12

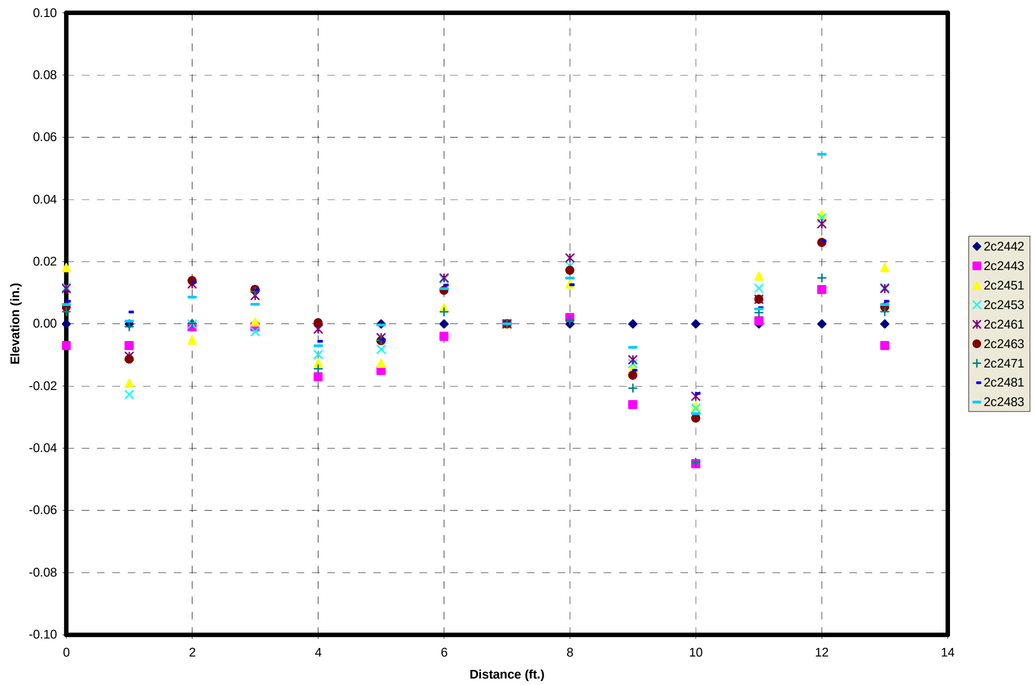

Figure C44. Level C profiles path 4, slab 12

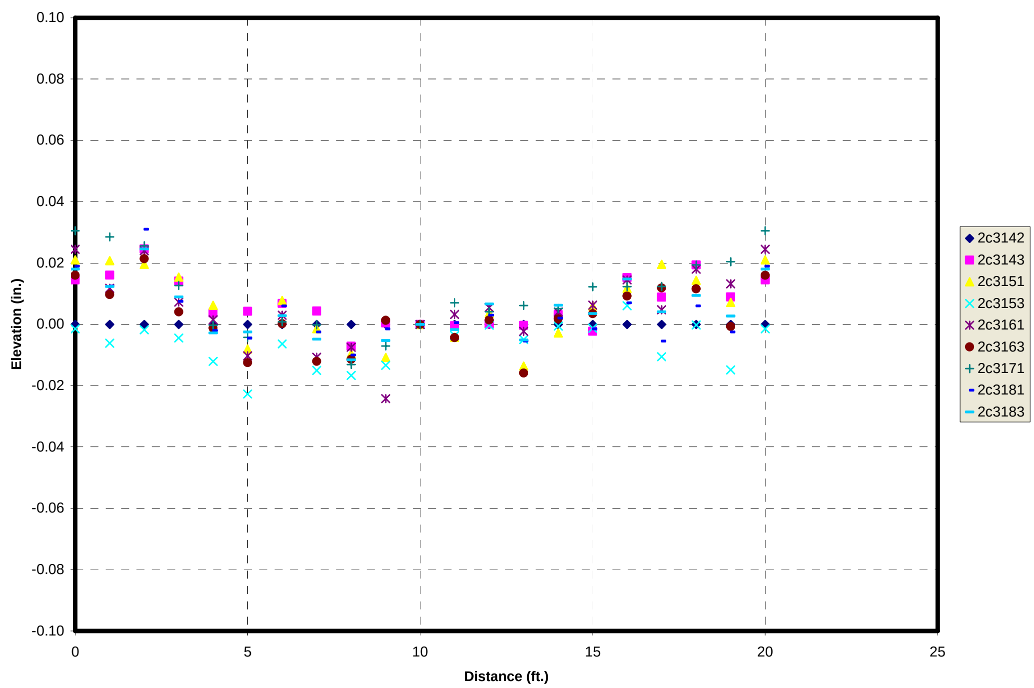

Figure C45. Level C profiles path 1, slab 13

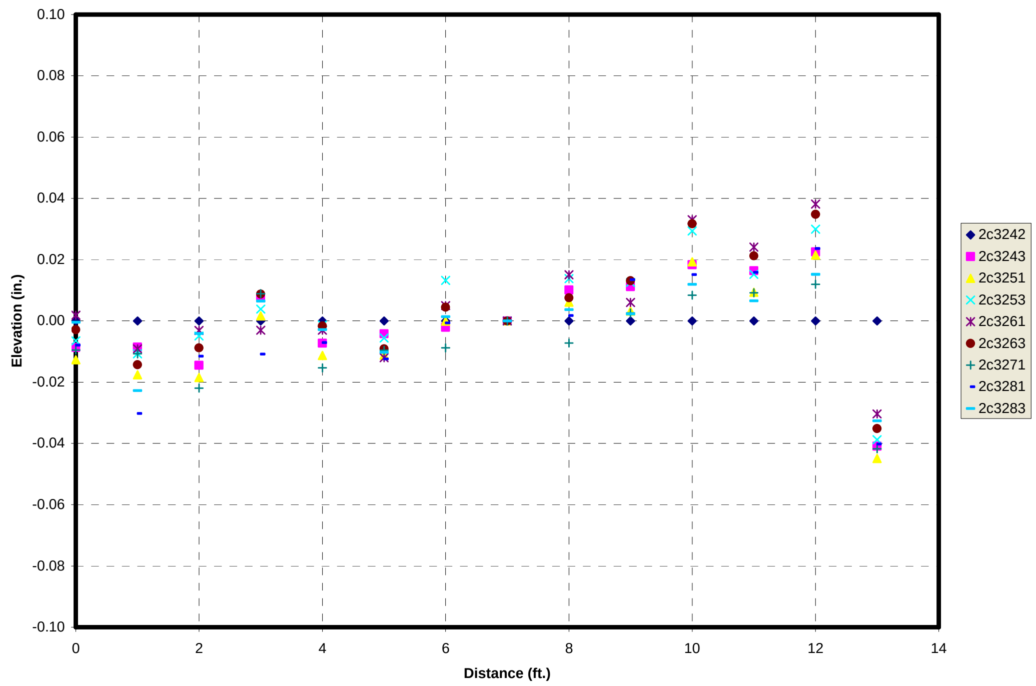

Figure C46. Level C profiles path 2, slab 13

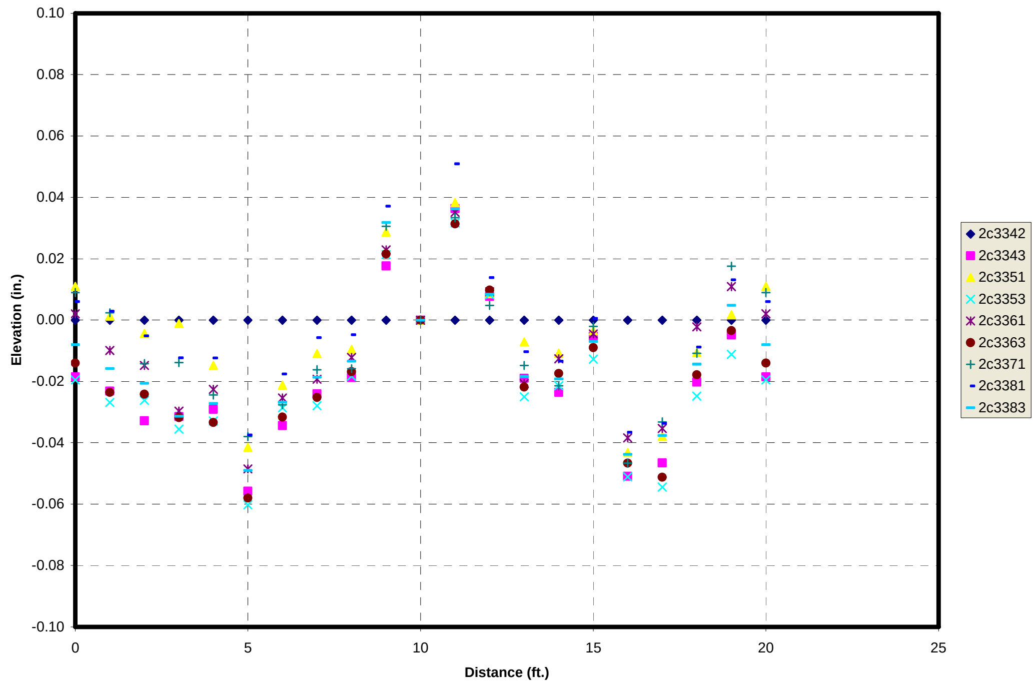

Figure C47. Level C profiles path 3, slab 13

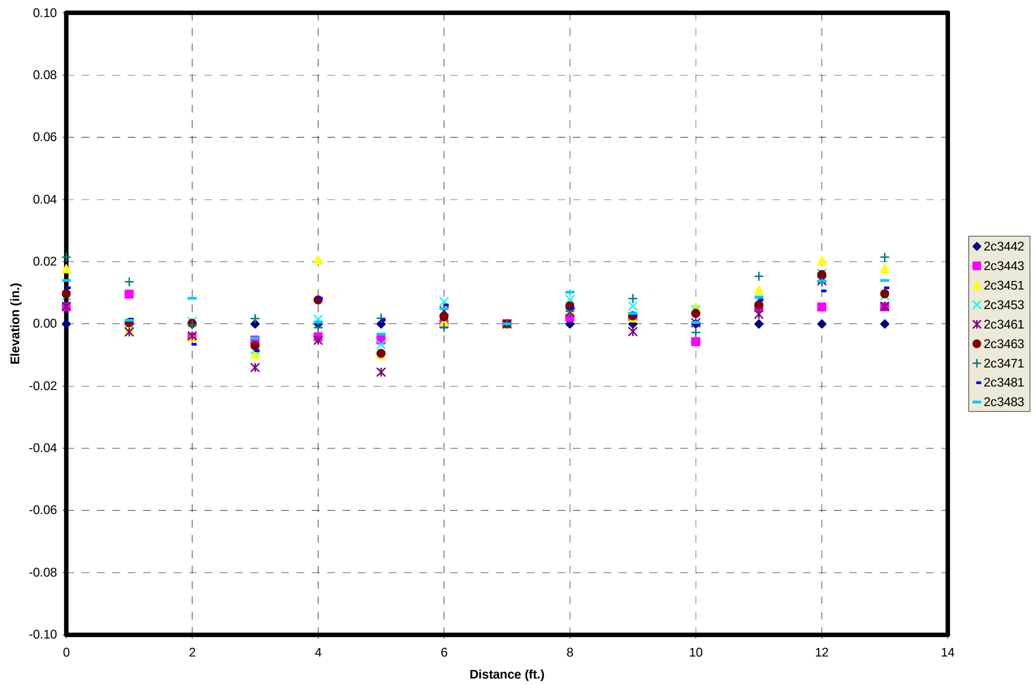

Figure C48. Level C profiles path 4, slab 13

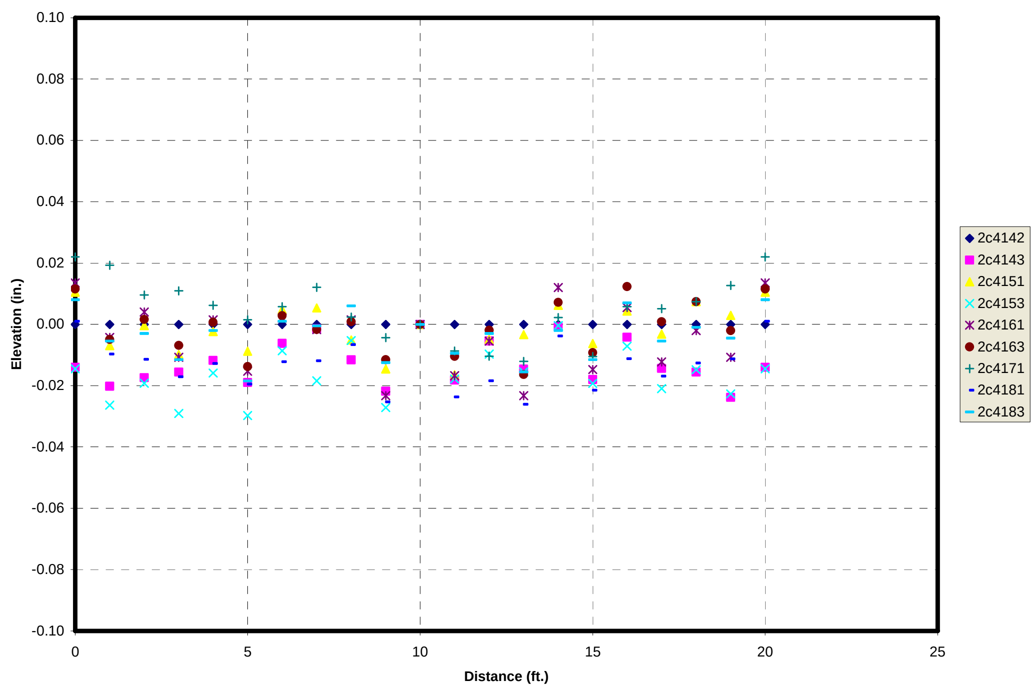

Figure C49. Level C profiles path 1, slab 14

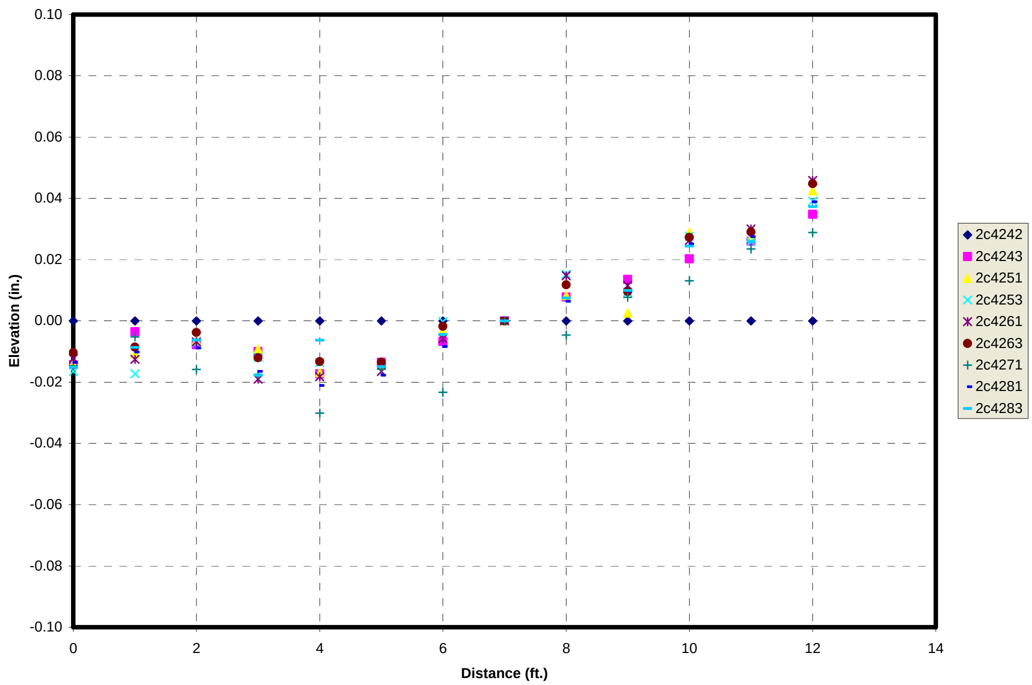

Figure C50. Level C profiles path 2, slab 14

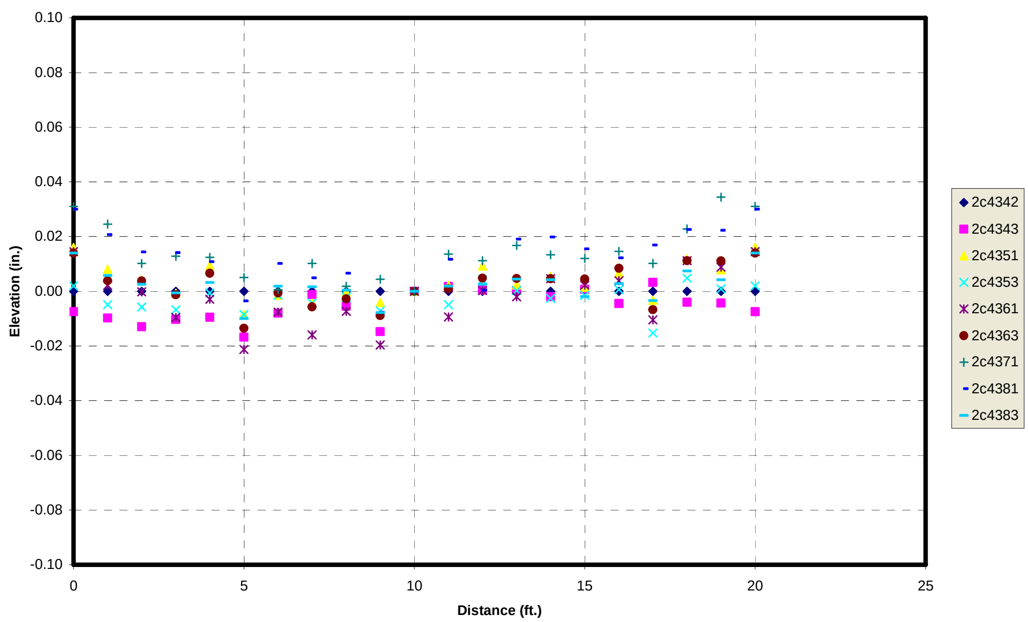

Figure C51. Level C profiles path 3, slab 14

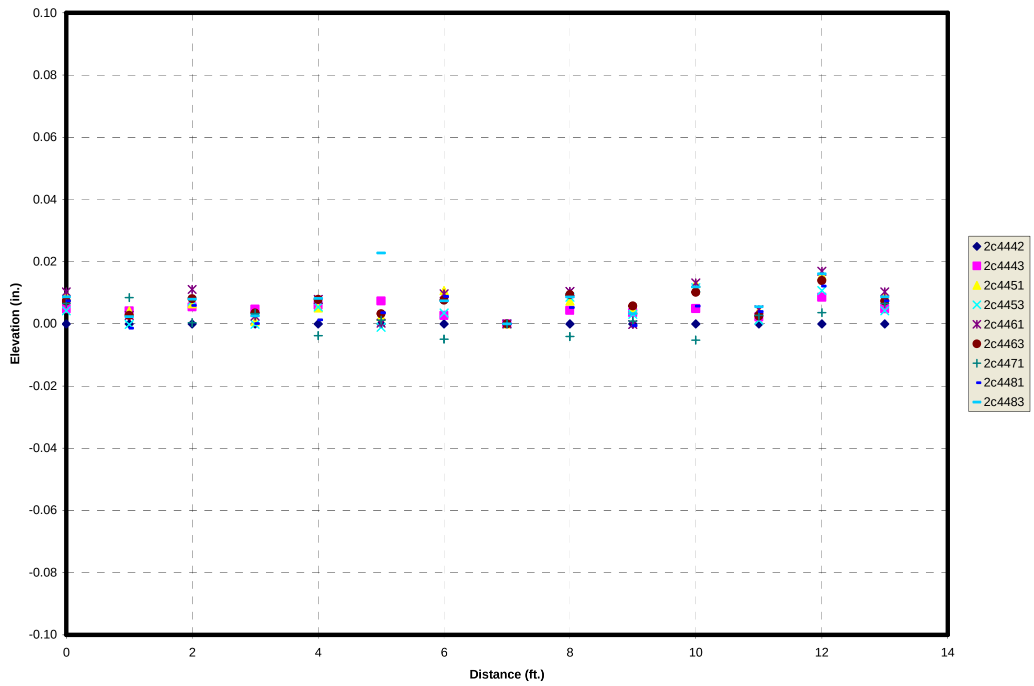

Figure C52. Level C profiles path 4, slab 14