Evaluation of HPC Pavement in Nelsonville, Ohio, using Non-destructive Methods

Shad Sargand[1], Mark Swanlund[2], Julian Bendana[3] and Daniel Castro[4]

Abstract

This paper is focused on evaluating the performance of several concrete mixes of high-performance concrete (HPC) pavement using different techniques such as laboratory testing, warping and curling monitoring and falling weight deflectometer testing. A research plan was developed to accomplish two principal objectives: First, to determine the maturity function of the newly placed concrete, and second, to monitor dynamic and environmental response of concrete slabs in each of three test sections. Each test section was approximately 1,000 feet long. Five hundred feet of each test section were cured using a spray-on membrane, while the other five hundred feet were cured using wet burlap. Three Concrete mixes using different types and sizes of coarse aggregate and granulated blast furnace slag were incorporated into this project. Two slabs in each test section were instrumented with thermocouple sticks at the center and outside corners.

Introduction

Nelsonville, Ohio, a quaint town with a population of about 4,560, is located in Athens County 100 km (60 miles) southeast of Columbus. Until recently, a dilapidated two-lane road called Canal Street (US 33) was Nelsonville's main throughway. The road was rapidly becoming inadequate to handle heavy truck loads traveling to the larger cities of Lancaster and Columbus. The Ohio Department of Transportation (ODOT) decided to reconstruct the 5.80 km (3.61 miles) of this road passing through the heart of Nelsonville.

A research plan was developed by the Ohio Research Institute for Transportation and the Environment (ORITE) at Ohio University in conjunction with the Ohio Department of Transportation (ODOT) to accomplish two principal objectives: First, to determine the maturity function of the newly placed concrete, and second, to monitor dynamic and environmental response of concrete slabs in each of three test sections. Each test section was approximately 305 meters (1,000 feet) long. Five hundred feet of each test section were cured using a spray-on membrane, while

[1] Russ Professor, Department of Civil Engineering, Ohio University, Athens, OH 45701, email: ssargand@bobcat.ent.ohiou.edu
[2] Federal Highway Administration, 400 Seventh Street SW, Washington DC 20590, email: mark.swanlund@fhwa.dot.gov
[3] New York State Department of Transportation, 1220 Washington Avenue, Albany, NY, email: jbendana@dot.state.ny.us
[4] Assistant Professor, Department of Civil Engineering, Ohio University, Athens, OH 45701, email: dcastro@bobcat.ent.ohiou.edu

the other five hundred feet were cured using wet burlap. The following parameters were monitored in the PCC slabs: Temperature profile during curing with thermocouples, temperature as a function of time for maturity testing, slab shape with Dipstick and a stationary profiler, slab shape using the ODOT profiler traveling at highway speed, slab shape using an ORITE profilometer, joint movement as a function of time and slab deflection during non-destructive testing. Three concrete mixes using different types and sizes of coarse aggregate were incorporated into this project, as shown in Table 1.

Table 1. Summary of concrete mixes used on US33

MIX	A	B	C
Aggregate	No. 57	No. 357	ODOT
Slag	30%	30%	Normal

Section Layout

Two slabs in each test section were instrumented with thermocouple sticks at the center and outside corners. Figure 1 illustrates the location of each test section and the location of the thermocouples. Each thermocouple stick consisted of four T Type thermocouples spaced evenly from top to bottom.

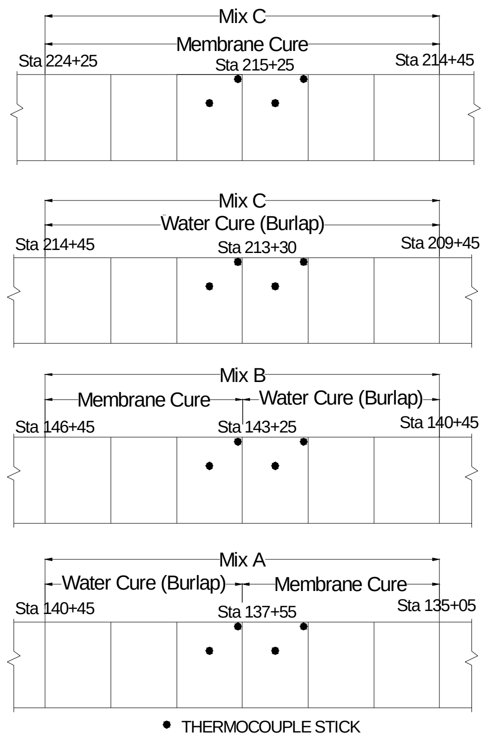

Figure 1. Section layout

Maturity Methods

A maturity function for the experiment was established by replicating each mix and cure type at the ORITE laboratory, and then testing cylinders and beams made from the lab batches of concrete for strength. Slab profiles were measured with a dipstick and ORITE profilometer to monitor warping and curling. Two methods of predicting concrete strength were adopted. The first is the Nurse-Saul equation, which uses simple linear integration. This method does not properly address temperature vs. time plots with curving slopes that fluctuate with time. The second procedure for estimating concrete strength is the Arrhenius method, which uses the reaction rate of cement to compute an equivalent age factor from the recorded temperature history of the concrete (ASTM 1998). To establish maturity functions for the three different mixes used on US 33, approximately 290 cylinders and beams were prepared, cured, and monitored under controlled conditions at the ORITE materials testing laboratory in Athens, Ohio.

Laboratory Testing. To replicate mixes in the field, concrete was mixed with a 0.25 cubic meter (9 cubic foot), gasoline powered, concrete mixer. Standard 152 millimeter (6 inch) diameter by 305 millimeter (12 inch) tall, wax coated, cardboard cylinder molds were used to make concrete cylinders following ASTM C192 standards. Concrete beams were made using 152 millimeter (6 inch) by 152 millimeter (6 inch) by 533 millimeter (21 inch) plastic beam molds using ASTM C78 standards. The samples were cured in a temperature and moisture controlled chamber. For each batch that was being cured in the chamber, two extra cylinders were made and instrumented with one thermocouple inserted into the center of the cylinder. Air temperature was also recorded using a Campbell Scientific Model 107 temperature probe placed inside the chamber.

US33 Mix Replication Data. A beam-breaking apparatus was fabricated and mounted on a Material Testing System (MTS) compression machine where the user could capture loads from the MTS control module. Compressive strength of the de-molded cylinders was found using a 4,448 Kilo-Newton (1,000,000 pound) compression machine. The compression force and strength were captured by the control panel and recorded by the user.

This research project included three different mixes, including two mixes containing ground granulated blast furnace slag (GGBFS). The first mix contained slag used #357 coarse limestone was identified as Mix B. The second mix containing slag used #57 coarse limestone was identified as Mix A. The third mix, which was a standard Class C mix containing Type I cement, was identified as Mix C. The mix designs are shown in Table 2.

Table 2. US33 mix design

	Mix A		Mix B		Mix C	
	Slag 280 kg/cm^2 (4000 psi) #57's		Slag 280 kg/cm^2 (4000 psi) #357's		Standard 280 kg/cm^2 (4000 psi)	
	SSD Weight	Volume	SSD Weight	Volume	SSD Weight	Volume
Cement Type I	175 kg (385 lbs)	0.06 m^3 (1.96 ft^3)	175 kg (385 lbs)	0.06 m^3 (1.96 ft^3)	250 kg (550 lbs)	0.08 m^3 (2.80 ft^3)
Slag Cement (GGBFS)	165	0.91	165	0.91		
Coarse - #57 Limestone	1750	10.46	1750	10.46	1750	10.46
Sand	1300	8.07	1300	8.07	1300	8.07
Water	250	4.01	250	4.01	250	4.01
Admixture, Type A or D	0.68 kg (22.0 oz)		0.68 kg (22.0 oz)		0.68 kg (22.0 oz)	
Air Entrainment (6 +/- 1%)	as required	1.62	as required	1.62	as required	1.62
Slump	10 cm (4") max		10 cm (4") max		10 cm (4") max	
W/C Ratio	0.45		0.45		0.45	

Mixing and Batching. Each mix had cured temperatures of 5, 20, and 40° C (41, 68, and 104° F). For each mix at each temperature, samples were tested at 1, 3, 7, 14 and 28 days. Three samples were made for each test time in case a sample was faulty so that an average could be computed. Beams were made to ascertain flexural modulus and cylinders were made to determine compressive strength. Due to the size and number of beams and cylinders, only two mixes could be cured at a time. For each batch, two extra cylinders were instrumented with thermocouples for temperature measurement. Using the above outlined procedure, a total of 288 samples were made as illustrated in Figure 2.

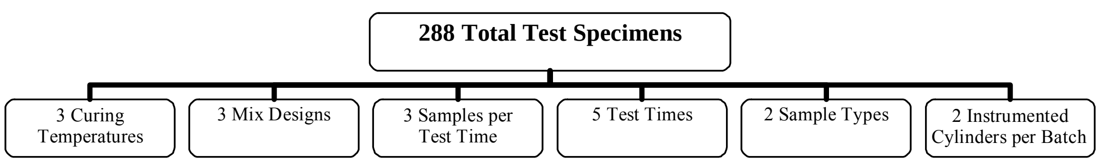

Figure 2. Test specimen diagram

The mixes were made to exact proportions provided by Smith Concrete of Marietta who provided concrete for the project. Each batch, which was approximately 0.17 m^3 (6 ft^3), was mixed according to ASTM C192 standards. A slump cone was used to measure the slump of each mix and an air meter was used to measure air content. The slump and air content were adjusted accordingly to meet mix design specifications by adding water or air entrainment additive, respectively. Test specimens were then molded using ASTM C470 standards. The specimens were immediately smoothed off with a trowel and placed in the environmentally controlled chamber for curing.

Specimen Testing. When it was time to test some specimens, they were removed from the chamber and de-molded. To ensure the tops and bottoms of the cylinders were flat, both ends were capped using capping compound. Each specimen was then tested in accordance with ASTM C39-94 and discarded appropriately.

Data Interpolation. Using time and temperature data collected from the lab and the field, maturity functions were plotted using Microsoft® Excel. Both the Nurse-Saul and the Arrhenius methods were evaluated in this comparison. The methods and results are presented in the following sections. During lab experiments, the value for k was adjusted until the data best fitted the laboratory results. The results of the rate constants and β value determination are presented in Table 3.

Table 3. Arrhenius constants

Mix	β	K
B	1.119048	0.3
A	1.071429	0.5
C	1.119048	0.3

Discussion of Maturity Results. All three mixes revealed similar tendencies with both the Arrhenius and Nurse-Saul methods over predicting strength in the field, as indicated in Figures 3, 4 and 5.

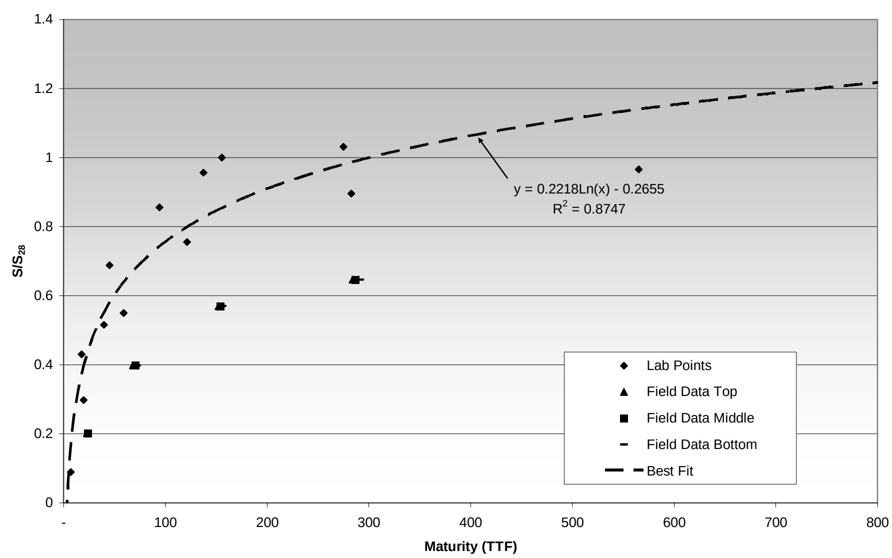

Figure 3. Nurse-Saul maturity method, Mix A, center of slab

Although the Nurse-Saul method produced better fitting results than the Arrhenius method, the fact that it uses the time-temperature factor limits its utility in real life applications. The Arrhenius method could be better applied if larger batches could be obtained from the mixing plants, rather than mixing small batches in the laboratory. Cylinders cast in the field could not be placed next to the slab, which means they most likely experienced different temperatures than the slab. Also, because less than one-third of a yard was mixed in the lab compared to eight or nine yards at a time in the field, curing properties could have varied somewhat. Any combination of these problems could account for bad predictions from the laboratory data.

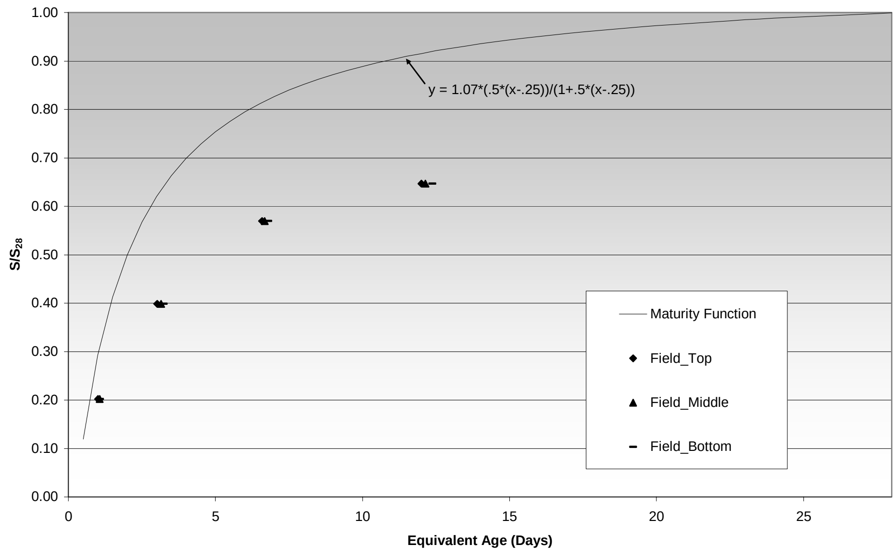

Figure 4. Arrhenius maturity method, mix A, field data, center of slab

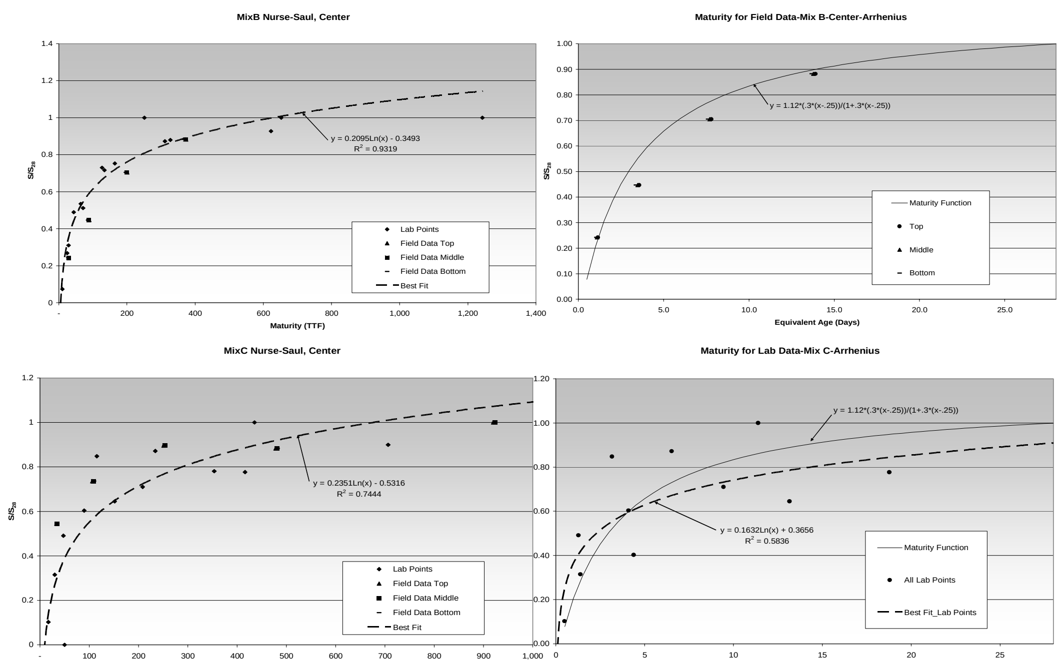

Figure5. Nurse-Saul and Arrhenius maturity methods for mixes B and C.

The ORITE Profilometer

The ORITE profilometer measures pavement elevation relative to an integral guide rail every half inch of distance over a maximum travel distance of 2.85 m (112 in) over pavement. The elevation measurement least count is approximately 0.001 cm (0.005 in). The angle of the profilometer guide rail with respect to horizontal is measured for each profile using a servo inclinometer reading to 0.001 degree. This permits contiguous profiles to be concatenated virtually into one. The elevations are measured by rolling a two-inch diameter by 9/16 inch wide ball bearing "follower" over the pavement. The bearing is at the end of an arm connected to an incremental optical rotary encoder and one increment represents about 0.001 cm (0.005 in) of change in elevation of the bearing.

An approximately 5 kilobyte ASCII disk file is produced for each profile. It records basic setup constants for the profile, the angle of the guide rail with respect to horizontal, and a variable number of observations, each consisting of an elevation and accumulated distance along the pavement. A maximum of 210 observations can be recorded, representing a 112-inch profile. The aluminum profilometer frame is about 3.35 m (11 feet) long. A notebook computer, used for controlling the instrument and collecting data, is supported at about waist height for convenience in reading the screen. A small 12-volt gel electrolyte battery and a 12VDC/115VAC inverter supply power to the components for a limited time of complete portability. Large, easily retractable wheels facilitate moving the instrument from place to place.

Method of Measurement, First Test Section as Example. Sets of contiguous 112-inch profiles sufficient to span each test section were recorded with the profilometer. Profiles were run as close to the outside (right) edge of the pavement slab as possible, with the outside feet of the profilometer two inches inside the slab. The positions of the beginning and ending elevations of each 2.85 m (112 in) profile with respect to the slab joints were recorded. To form a continuous profile of the entire test section, the first profile was rotated about its first elevation according to the inclinometer beam angle reading. Each successive profile was translated vertically by adding a constant to all 210 elevation readings so that the beginning elevation equaled the final elevation of the previous profile. Because these two elevations represented the same point on the pavement, one was discarded. Then the subsequent profile was rotated about the matched elevation point according to the beam angle reading. This was continued until the whole set of profiles was unified. One set of profiles was run in the morning as soon as the lane was closed to traffic and a second set was run about four hours later. The pavement temperature at several points was recorded with thermocouples embedded (cast) in the pavement and the surface temperature was recorded with a Raytek infrared "gun." Between the two tests, the weather went from cool and rainy to warm and sunny. At the fourth test section in the morning session, the profilometer failed after the first profile; therefore only about 2/3 of the first slab of this test section can be evaluated for warping.

Special procedures are required to minimize drift in the inclinometer whose readings are used to concatenate adjacent profiles. Due partly to the adverse weather in the morning and partly to the need for haste, the results were imperfect, so that the beginning and ending elevations of the morning and afternoon concatenated profiles apparently do not match, i.e., the gain or loss in elevation over the whole profile is different for the pair by up to 0.38 cm (0.15 in) over 20 m (65 ft). This effect increased as time went on during measurement. Nevertheless, it is the "fine structure" of a plot of the differences between respective elevations in the morning and afternoon profiles that reveals slab deformation, when the locations of the slab joints are superimposed on the plot. This will be illustrated using the first test section as an example.

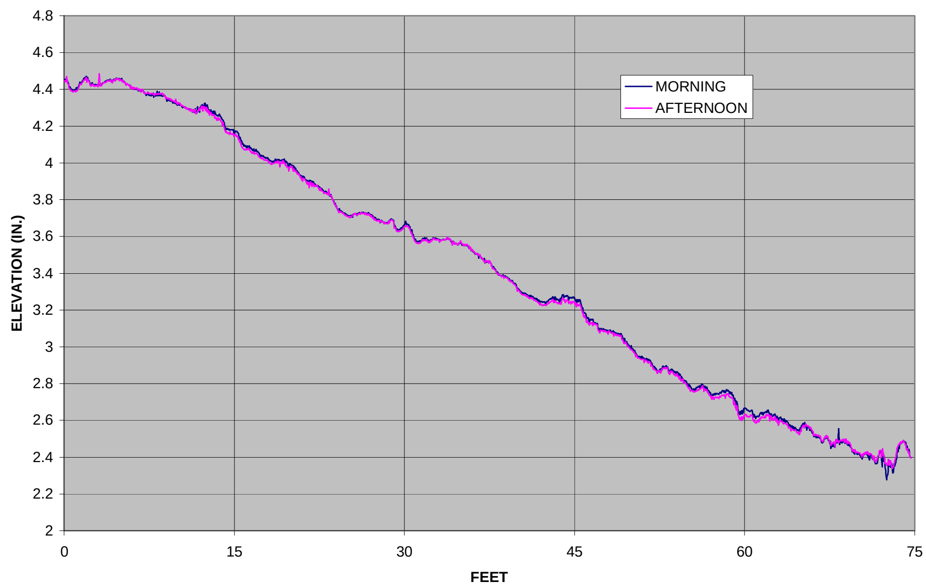

Figure 6. Morning and afternoon concatenated profiles for the first test section

The two concatenated profiles on the first test section are shown in Figure 5. This represents five slabs. Joints occur at x = 0, 4.5 m (15 ft), 9.1 m (30 ft), 13.7 m (45 ft), 18.3 m (60 ft) and 22.9 m (75 ft). The change (fall) in elevation from start to end of the five slabs is about 5 cm (2 in). No translation was needed to join the beginning elevations of the two profiles. The elevations of the two profiles at x = 22.9 m (75 ft) are practically equal for this test section. The warping of each slab can barely be detected by the slight rise of the afternoon profile between the joints relative to the morning. The vertical datum for the elevation is arbitrary and is established by the profilometer so that no position of the ball bearing "follower" will produce a negative elevation.

Development of a Measure of Warping or Curling. Curling and warping generally describe slab deformations caused by temperature and moisture gradients, respectively, in concrete slabs. Higher temperature and/or higher moisture in the bottom of the slab cause it to develop an upward concave shape and, conversely, higher temperature and/or moisture at the top of the slab cause it to develop a downward concave shape. While this concept is somewhat idealistic, it does provide a useful methodology for describing how concrete slabs respond to environmental factors.

The shape of the longitudinal slab profile along a line can be precisely described by the profilometer. The precision might be on the order of 0.03 cm (0.01 in), but that remains to be proven by repeated measurements and some sort of control. Profiles made along closely-spaced parallel lines could be used to develop a three-dimensional surface.

The easiest way found so far to visualize slab curling is to plot the difference between the morning and afternoon profiles point by point along the profile. Curl will appear in the shape or curvature of this "difference function" provided that the shape is not embedded in the "noise" caused by (a) the fine structure of the pavement, (b) the 0.001 cm (0.005 in) least count of the profilometer's elevation sensor, and (c) the inevitable mismatch between actual paths taken by the ball bearing follower. Figure 5 shows the difference between the morning and afternoon profiles for the first test section. The respective morning elevations have been subtracted from the afternoon elevations so that the curvature between the joints at different distances is concave downward, meaning that the center of the slab rose with respect to the ends as heat was absorbed by the pavement surface.

The minima at the joints are obvious, and the amount of warping, taken as the difference in elevation between the peaks and lines drawn between the joints, is on the order of 0.05 cm (0.02 in) inches. Recall that the least count of the profilometer elevation measurement is 0.001 cm (0.005 in). The reasons why the plots do not show a 0.001 cm (0.005 in) "granularity" (i.e., do not appear as a step function with steps equal 0.005 inch) are: Firstly, the profilometer evaluates elevation every one-half inch (approximately) by averaging ten readings of the rotary encoder. For each recorded elevation five readings are made successively over a short (0.3 cm to 0.6 cm) distance as the ball bearing follower moves along the guide rail toward the "far" end and the process is repeated at the same place for each elevation as the follower returns to the starting end of the guide rail. The encoder produces a count for each reading, an integer, and one count represents about 0.001 cm (0.005 in) change in elevation of the ball bearing follower. When the ten counts are averaged, a floating point number is generated representing the set of readings. For example, if five of the ten readings translate to an elevation of 0.0025 cm (0.001 in) and five translate to an elevation of 0.005 cm (0.002 in), the elevation is recorded as 0.0034 (0.0015 in). Secondly, the beginning and ending (longitudinally on the slab) of each 2.84 m (112 in) profile is not practically reproducible within about 1/8 inch in the field, especially when one is pressed for time. Therefore, when dirt or isolated small textural features on the surface are present and do not cancel each other in the difference between the morning and afternoon profiles, a "spike" results. Finally, the lateral placement of the profile is not reproducible within about 0.64 cm (¼ inch), with the same consequence as above.

Concatenated Profiles; Test Sections Two, Three and Four. The concatenated profile for the second test section is shown in Figure 6. Eight slabs are represented, plus about 3 m (10 ft) of the ninth slab. The drift in the inclinometer ran in both senses, so that the loss in elevation was the same for morning and afternoon profiles. The difference function, Figure 6, shows the drift as an overall rise in the middle of the curve, returning to about zero at the end of the profile. The loss of elevation for this set of slabs is about 8 cm (3 in). One profile was translated to match the beginning elevation of the other.

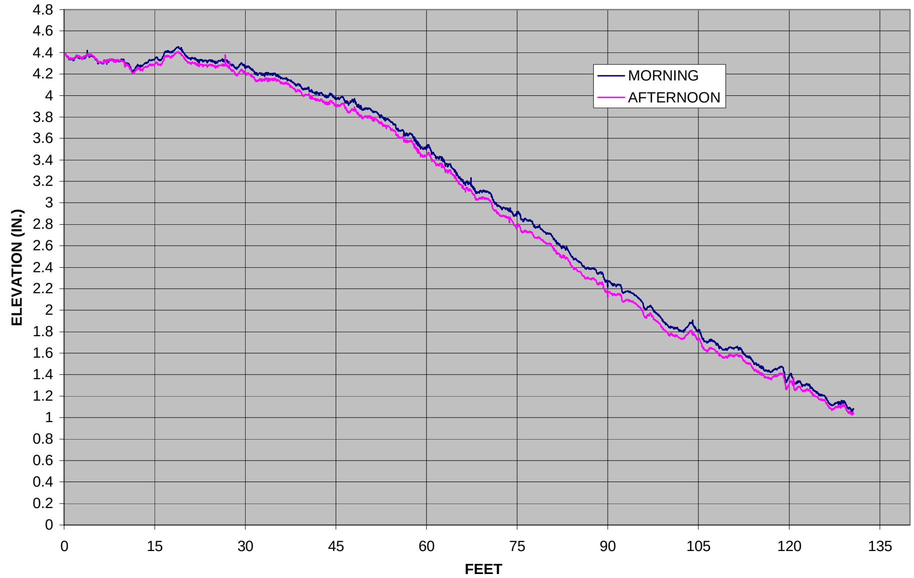

Figure 7. Morning and afternoon concatenated profiles for the second test section

The worst case of inclinometer drift for the day is illustrated in Figure 7, showing morning and afternoon profiles over the slabs of the third test section. No translation was done. The rise in elevation from the beginning to the end of the four slabs is about 6.6 cm (2.6 in). The ending elevations differ by about 0.381 cm (0.15 in).

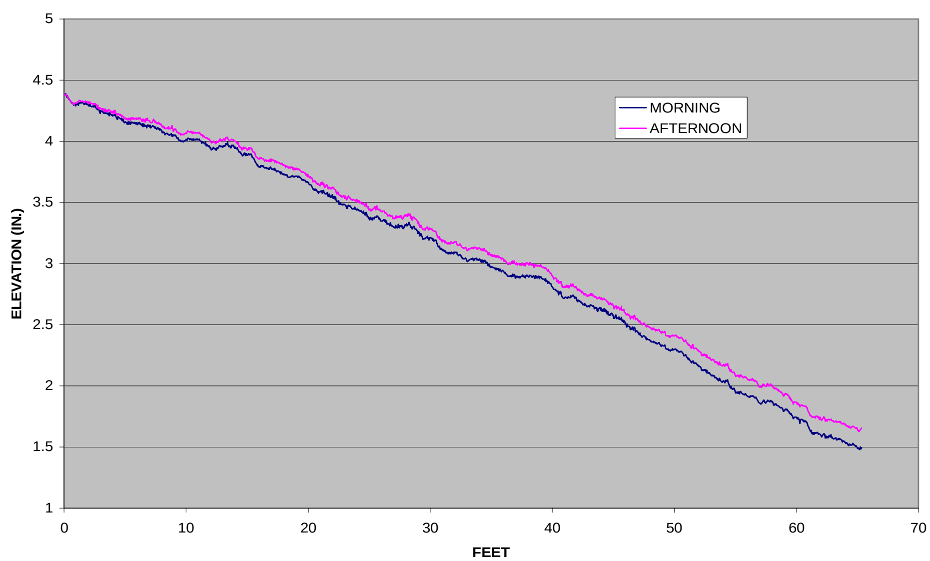

Figure 8. Morning and afternoon concatenated profiles for the third test section

Results. Moving average trend lines (n = 20) were added to the charts of the difference functions for the four test sections, as described in Figures 5 through 7.

Table 4 shows the estimated "greatest displacement of the center portion of the slab profile relative to a line between the elevations at the joints," which was defined as the measure of warp. The displacements were gauged visually along a vertical line from the maxima to a line connecting the elevations at the joints. In cases where the maximum was ambiguous or appeared spurious, the peak nearest the center of the slab was used as the maximum. The difference function for the fourth test section is a special case; the value for warp was taken as the highest elevation difference minus the lowest.

Table 4. Estimated warp of individual slabs, inches

Test Section		Slab Number								
		1	2	3	4	5	6	7	8	Mean
First (A)	Membrane cure	0.022	0.018	0.021						0.020
	Water cure				0.021	0.023				0.022
Second (B)	Water cure	0.025	0.017	0.020	0.012					0.019
	Membrane cure					0.022	0.020	0.013	0.010	0.016
Third and Fourth (C)	Water cure	0.026	0.012	0.026	0.028					0.023
	Membrane cure	0.027	N/A	N/A	N/A					0.027

Falling Weight Deflectometer Measurement

Falling Weight Deflectometer (FWD) measurements were obtained on the new PCC pavement on US 33 in Nelsonville to determine vertical deflection of the slab ends and load transfer across the joints in the morning and afternoon of March 24, 2004. These measurements are shown in Table 5. One set of measurements was run in the morning while the pavement temperature was uniform, and a second set of measurements was run in the afternoon after the pavement surface had warmed and a positive temperature gradient had built up in the pavement. The morning run started at 8:22 am and the afternoon run started at 2:34 pm. Both runs required about two hours to complete. Infrared thermometer readings indicated the surface temperature ranged from 42º – 44º F. in the morning and from 60º – 61º F. in the afternoon.

Geophone Df1 of the FWD was at the center of the 300 mm (11.8 in.) diameter load plate, Geophone Df2 was 305 mm (12 in.) behind the center of the load plate, and Geophone Df3 was 305 mm (12 in.) in front of the center of the load plate. Table 7 summarizes the normalized maximum deflection (Df1) in mils/kip and load transfer (LT) in percent as the FWD load plate was placed in the approach and leave positions at five joints in each of the six test sections, each representing a different mix and curing method combination. In the approach position, the load plate was located behind the joint and load transfer was calculated as Df3/Df1. In the leave position, the load plate was located just beyond the joint and load transfer was calculated as Df2/Df1.

Table 5. ATH33-Nelsonville FWD measurements 3/24/04

Section	Curing	Joint	Morning				Afternoon			
			Approach		Leave		Approach		Leave	
			$Df1_A$ (mils/kip)	LT_A (%)	$Df1_L$ (mils/kip)	LT_L (%)	$Df1_A$ (mils/kip)	LT_A (%)	$Df1_L$ (mils/kip)	LT_L (%)
A	Water	6	0.45	86.4	0.42	89.1	0.40	94.4	0.42	86.4
		7	0.46	91.1	0.44	91.6	0.40	96.2	0.43	90.2
		8	0.66	91.5	0.78	79.1	0.58	81.6	0.51	91.0
		9	0.51	90.1	0.56	81.0	0.38	86.8	0.40	81.7
		10	0.60	86.3	0.56	89.2	0.43	96.0	0.48	85.8
		Avg.	0.54	89.1	0.55	86.0	0.44	91.0	0.45	87.0
	Membrane	1	0.42	93.9	0.39	100.7	0.42	93.3	0.40	96.5
		2	0.44	90.1	0.44	89.6	0.38	93.9	0.38	92.8
		3	0.51	86.3	0.52	85.1	0.51	82.7	0.44	89.1
		4	0.38	91.1	0.38	92.1	0.32	91.1	0.31	88.0
		5	0.41	92.8	0.43	87.3	0.36	98.3	0.42	82.4
		Avg.	0.43	90.8	0.43	91.0	0.40	91.9	0.39	89.8
B	Water	1	0.36	96.8	0.36	94.5	0.31	94.8	0.32	92.0
		2	0.43	92.0	0.41	94.3	0.37	92.9	0.36	100.0
		3	0.38	96.9	0.40	90.0	0.32	97.1	0.33	96.0
		4	0.38	92.0	0.36	96.7	0.32	94.2	0.32	92.9
		5	0.37	90.5	0.34	101.5	0.29	94.3	0.28	95.0
		Avg.	0.38	93.6	0.37	95.4	0.32	94.7	0.32	95.2
	Membrane	6	0.31	90.5	0.29	95.9	0.28	89.6	0.26	93.4
		7	0.32	92.4	0.31	93.3	0.28	95.6	0.29	88.5
		8	0.35	90.0	0.35	87.3	0.35	92.4	0.35	87.9
		9	0.37	93.2	0.38	91.8	0.35	94.3	0.33	93.6
		10	0.35	95.4	0.36	88.2	0.35	92.4	0.34	93.9
		Avg.	0.34	92.3	0.34	91.3	0.32	92.9	0.31	91.5
C	Water	1	0.49	87.8	0.49	87.0	0.41	92.3	0.42	89.6
		2	0.41	87.7	0.38	92.9	0.35	90.5	0.33	94.8
		3	0.34	92.7	0.34	89.4	0.30	92.6	0.30	91.5
		4	0.49	94.7	0.52	89.0	0.38	95.1	0.39	90.9
		5	0.30	96.1	0.33	87.8	0.26	93.8	0.27	90.3
		Avg.	0.41	91.8	0.41	89.2	0.34	92.9	0.34	91.4
	Membrane	6	0.44	91.8	0.45	87.9	0.40	92.6	0.39	92.2
		7	0.52	92.3	0.50	93.7	0.43	94.1		
		8	0.52	93.3	0.53	89.0	0.44	90.0	0.45	89.6
		9	0.58	97.8	0.62	88.6	0.41	98.8	0.45	90.5
		10	0.59	94.4	0.61	89.9	0.44	96.9	0.49	91.1
		Avg.	0.53	93.9	0.54	89.8	0.42	94.5	0.45	90.9

In general, maximum deflection and load transfer were about the same on all test sections when measured in the approach and leave positions. Data were quite consistent between the morning and afternoon runs, in that individual joints showing high or low readings in the morning showed similar trends in the afternoon. Load transfer was essentially the same on all sections and during both runs. Maximum deflection was higher on the water cured portion of Section A, about the same on both portions of Section B, and higher on the membrane cured portion of Section C.

As would be expected, deflections consistently dropped in the afternoon as the surface warmed and the slab ends curled downward to increase support under the PCC slabs. The percent decrease in deflection from morning to afternoon was highest on the five water cured joints in Section A and on all ten joints in Section C. Individual joints with the most drop in deflection were Joints 8, 9 and 10 in Section A, and Joints 4, 7, 8, 9 and 10 in Section C.

Conclusions and Discussion

The performance evaluation of three different HPC pavements was possible using different techniques. The research was aimed at determining the maturity function of the newly placed concrete and to monitoring the dynamic and environmental response of concrete slabs in each of three test sections. Three one-thousand-foot test sections were constructed on US Route 33 in Nelsonville using the following three concrete mixes: Mix A with 30% blast furnace slag cement and No. 57 limestone aggregate; Mix B with 30% blast furnace slag cement and No. 357 limestone aggregate; and Mix C which was a standard ODOT mix with no blast furnace slag cement and No. 57 limestone aggregate. Half of each test section was cured using wet burlap ("water cured"), and the other half was cured using a sprayed on membrane. The conclusions of the research are:

- Two equations describing maturation of concrete were evaluated, the Nurse-Saul method and the Arrhenius method. A total of 288 test cylinders were made in the laboratory using the same mix proportions that were used during construction, and these cylinders were matured in a climate chamber at 5°C, 20°C, and 40°C, and tested at 1, 3, 7, 14, and 28 days. The tests included compressive strength and modulus of rupture.
- Using the Nurse-Saul method, Mixes A and B had a datum temperature of 0° C and Mix C had a datum temperature of 10° C. The fit of the strength ratio S/S28 using the Nurse-Saul method varied with each mix: Mix B lab and field results both fit the curve well; Mix A lab results also fit well, but the field results were over predicted by 30%; Mix C data were scattered, but overall the predicted strength matched those of the field cylinders. The poor fit by the field data for Mix A may have been caused by the test cylinders being cured in the sun while the temperature sensors in the test section of the road were in the shade. It should also be noted that the Nurse-Saul method has limited applicability due to the use of a time-temperature factor.
- For the Arrhenius method, the reference temperature used was 23° C. The strength at 28 days was assumed to be 4000 psi and the age of final setting and start of strength development was 0.25 days. Based on these assumptions, values

of the rate constant k and the strength factor β were computed for each mix and curves were made comparing predicted strength ratios (S/S28) using this model to measured strength ratios of field and lab samples. Again, the strength of Mix A was over predicted by about 30%. The fits in general were not as good for each of the mixes. Some of this may be attributable to the possible differences between the small lab batch of concrete and the much larger field batch; the Arrhenius method may work better if samples were obtained from a larger batch of concrete at the mixing plant. Another possible source of discrepancy was the possible mixing of some of the Mix C with the quick set concrete used in the previous batch of concrete in the field.

- In summary, although the Nurse-Saul method produced better fitting results than the Arrhenius method, the fact that it uses the time-temperature factor limits its utility in real life applications. The Arrhenius method could be better applied if larger batches could be obtained from the mixing plants, rather than mixing small batches in the laboratory. Cylinders cast in the field could not be placed next to the slab, which means they most likely experienced different temperatures than the slab. Also, because less than one-third of a yard was mixed in the lab compared to eight or nine yards at a time in the field, curing properties could have varied somewhat. Any combination of these problems could account for bad predictions from the laboratory data.
- The average curling measured in Mix A slabs was 0.051 cm (0.020 in) for membrane cured concrete and 0.056 cm (0.022 in) for water cured concrete using the ORITE profiler. Average curling measured in the Mix B slabs was 0.048 cm (0.019 in) for membrane cured concrete and 0.041 (0.016 in) for water cured concrete. Average curling observed in the Mix C slabs was 0.069 cm (0.027 in) for membrane cured and 0.058 cm (0.023) in for water cured concrete. It should be noted, however, that the 0.069 cm (0.027 in) on the membrane cured slabs in Mix C is based on a measurement of about two-thirds of one slab because the profilometer broke down during the morning run.
- The water cured Mix B slabs showed the least curling, followed by the membrane cured Mix B. Mix C had the most curling, particularly the membrane cured slab, but again because of the limited data this may not be as significant as it appears.
- A Falling Weight Deflectometer was used to measure pavement deflections and load transfers at the joints. On all sections, approaching and leaving measurements of deflection at each joint agreed very closely, to $5.5\text{x}10^{-7}$ cm/kg (0.01 mils/kip) or less, except for the afternoon run with membrane cured Mix C. In both the morning and afternoon runs, membrane cured Mix B had the lowest deflection, $1.87\text{x}10^{-5}$ cm/kg (0.34 mils/kip) and $1.73\text{x}10^{-5}$ cm/kg (0.315 mils/kip) respectively, using an average of approaching and leaving values in each case. Water cured mix B had deflections that were almost as low, while water cured Mix A had the highest deflection, at $2.99\text{x}10^{-5}$ cm/kg (0.545 mils/kip) in the morning and $2.45\text{x}10^{-5}$ cm/kg (0.445 mils/kip) in the afternoon, followed by membrane cured Mix C. In all sections, the average deflection in the afternoon was less than that in the morning by 10-20%.
- Water cured mix B had the highest load transfer across the joint at 94.5% in the morning and 94.95% in the afternoon, again using the average of approaching and

leaving values. Water cured Mix A had the lowest load transfer at 87.55% in the morning and 89.0% in the afternoon. Load transfer measured in the afternoon was about the same as that measured in the morning for each section. As seen in the preceding discussion, Mix B had both the least deflection as measured by the Falling Weight Deflectometer and the least warping as measured by the profiler. The water curing produced a lower maximum curl, but the membrane cured section had a slightly lower deflection. In both tests, the other curing method for mix B produced the second best result. Thus it appears that Mix B is the most durable mix from a standpoint of experiencing the least loss of support. Either method of curing seems to work equally well with Mix B.

References

ASTM C 1074 (1998), "Practice for estimating concrete strength by the maturity method," 2000 ASTM Standards, Vol. 04.02, ASTM, West Conshohocken, PA.