Validation of Concrete Pavement Responses Using Instrumented Pavements

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Mechanistic based pavement design procedures require validated mathematical models and calibrated transfer functions. The transfer functions can be calibrated only by observing the performance of pavements over time. The mathematical models can be calibrated by comparing the fundamental pavement responses to load and climate with the responses predicted by mathematical models. Two instrumented pavement sections are described that were constructed in Illinois to validate the mathematical models used in the development of a mechanistic based pavement design procedure for jointed concrete pavements. The type and location of gauges and the material properties and testing procedures used are detailed. Typical results and the significance of results with respect to the analysis models used and the design procedure developed using the models are presented. Effects of bonding between the slab and the lean concrete subbase and the implications of tied portland cement concrete shoulders are demonstrated. Effects of temperature changes are shown to be a major factor in the responses of the pavements.

Over the past several years, the University of Illinois, under the sponsorship of the Illinois Department of Transportation, has developed mechanistic based procedures for jointed and continuously reinforced concrete pavements. Validation of the design procedure was one of the tasks included in the study, which included short- and long-term validation. The long-term validation involves a comparison of the actual pavement performance over a number of years versus the predicted performance. Short-term validation involved a comparison of actual pavement responses with responses predicted using the mechanistic models in the design procedure.

During the summer of 1986, as a part of the short-term validation, a number of jointed and continuously reinforced concrete (CRC) pavement test sections were instrumented at two locations in Illinois. Gauges were installed in 5 sections of CRC pavements and 22 sections of jointed pavements. A total of 16 different pavement sections were instrumented, with 11 of the jointed sections replicated. The instrumented sections included three slab thicknesses of the jointed and two of the CRC pavements, with four different joint spacings in the jointed pavements. Instrumented sections of both jointed and CRC sections had varying drainage characteristics.

Strains in the pavement sections were recorded at specified intervals starting as soon as possible after the concrete had initially hardened. After the concrete had reached its design strength, but before the pavements were opened to traffic, the pavements were loaded with static and moving loads by using a truck with an 18-kip single axle load. The data were first collected in the memory of a Compaq portable computer with 640K memory, quickly reviewed for potential errors, and then transferred to floppy disks.

Currently there are over 100 floppy disks (360K capacity) filled with data, and more are being collected. These data are being analyzed and evaluated as time permits. As a check on the recording equipment, strains in the concrete and steel under static loading were also read using an SR-4 strain indicator type N.

Preliminary evaluation of the data indicates that the analysis models used in developing the design procedure accurately predict the strains caused by load in the concrete pavement. Strains caused by temperature and moisture changes in the concrete are also significant in the performance of these pavements. These results indicate that both the relative and absolute strains caused by temperature and moisture changes in the pavement were, on the average, greater than expected. Interpretation of these data is very difficult because the pavements with the greatest thermal and shrinkage strains probably have the least restraint and hence the least stress, whereas those with the least strain probably have the greatest restraint and hence the greatest stress.

Details of the instrumentation installed in the pavements are described and the type of data available from the instrumentation package is presented. Procedures used to analyze the data and examples and implications of the findings to date are discussed.

PROJECT DESCRIPTION

Two instrumented demonstration projects were designed and constructed for validation of proposed design procedures for jointed plain concrete (JPC), jointed reinforced concrete (JRC), and CRC pavements in the state of Illinois. Demonstration project FA 409 was constructed near Carlyle, Ill., approximately 20 mi south of I-70 on US-50, and demonstration project FA 401 was constructed near Freeport, Ill., approximately 40 mi west of Rockford, Ill. on US-20. Layout of these projects along with details regarding joint layout, pavement thicknesses, pavement type, and drainage conditions at the project sites are shown in Figures 1 and 2 and are reported elsewhere (*1*). The strain gauges were installed during the construction phase to monitor the effects of wheel load and temperature-induced strains. Table 1 summarizes the instrumented slabs at each project site.

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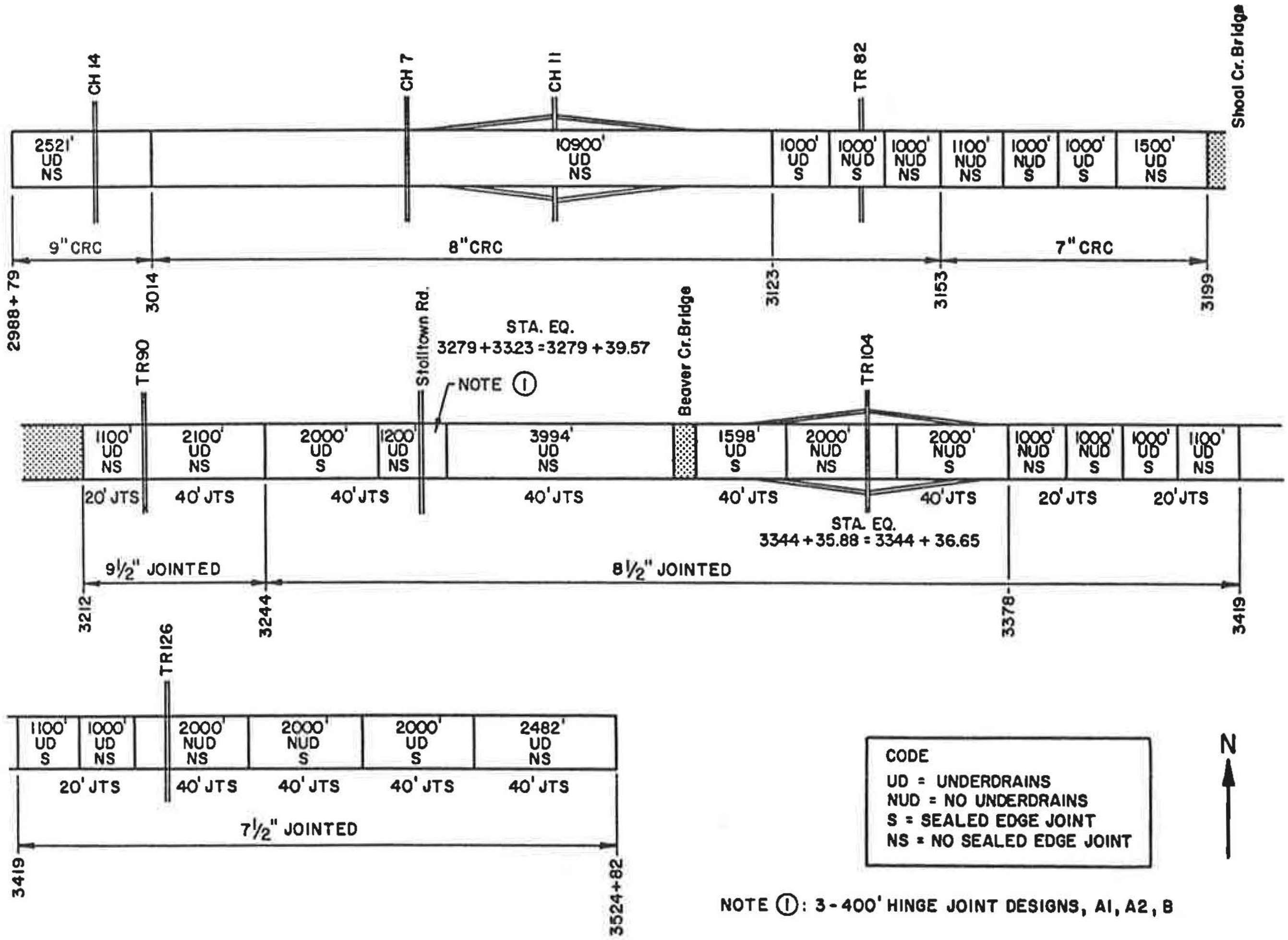

FIGURE 1 Carlyle, Illinois, demonstration project layout.

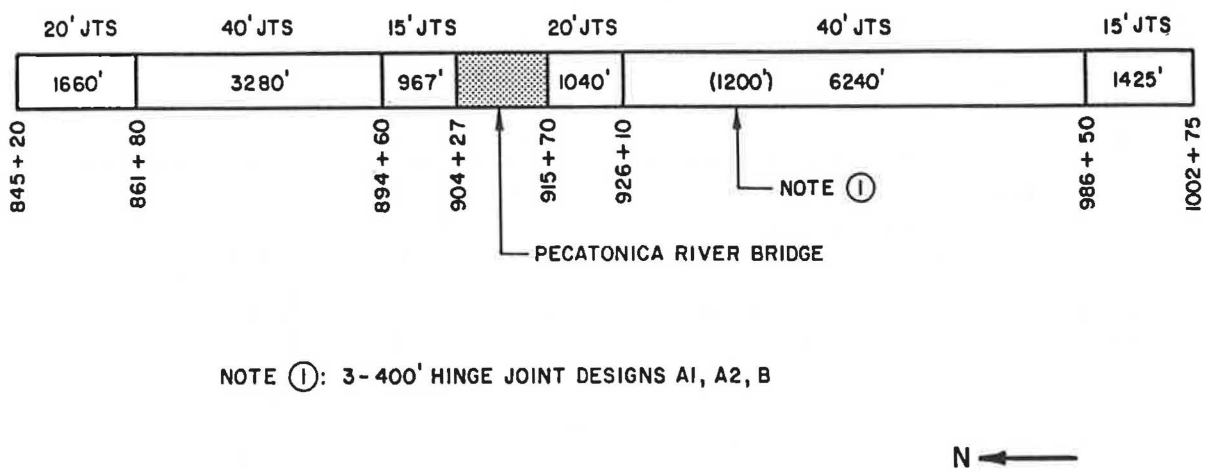

FIGURE 2 Freeport, Illinois, demonstration project layout.

TABLE 1 SUMMARY OF GAUGES IN JOINTED PAVEMENTS

Location	Station	Joint Spacing	Thickness	# of Gauges	Joint Type	Ref Fig
Carlyle	3216+08	20′	9-1/1"	5	dowel	4
	3218+68			5	"	4
	3226+08	40′		12	"	6
	3229+88			12	"	6
	3264+91	20′(A1)	8-1/2"	13	hinge	7
	3266+91			13	"	7
	3273+31	13′-4"(B)		13	"	5
	3274+91			13	"	5
	3432+06	20′	7-1/2"	5	dowel	4
	3439+06			5	"	4
	3485+66	40′		12	"	6
	3505+66			12	"	
Freeport	846+91	20′	10"	5	dowel	4
	875+46	40′		12	"	6
	896+05	15′		5	"	8
	970+10	20′		5	"	4
	927+30	20′(A1)		13	hinge	7
	292+70			13	"	7
	935+30	13′-4"(B)		13	"	5
	935+30			13	"	5
	985+27	40′		12	dowel	6
	999+87	15′		5	"	8

STRAIN GAUGE LAYOUT AND SLAB INSTRUMENTATION

Polyester-encapsulated wire-type electrical resistance gauges, Series "PM," manufactured by Tokyo Sokki Kenkyujo (PML-120 and PML-60 obtained through Texas Measurements, Inc.), were placed in the concrete. The wire-type strain gauge and lead wires were hermetically sealed between polyester resin plates, and the entire gauge was coated with a gritty substance to promote bonding to concrete.

To eliminate localized effects, the gauge length was chosen to span several aggregate particles. Since the maximum particle size in the portland cement concrete (PCC) was 1.5 in., a gauge length of 4.75 in. was selected.

The electrical conducting wires used in the strain gauges undergo a change in resistivity with changes in temperature. Another temperature effect is caused by the gauge being bonded to a test material (concrete) that has a different coefficient of thermal expansion than the resin gauge material. Therefore, a temperature compensation gauge or "dummy" gauge was installed in parallel with each active gauge. To maintain them in an "unstrained" condition, dummy gauges were placed in a polyvinylchloride (PVC) tubing, which was then sealed to prevent intrusion of the concrete, and the entire tube was cast into the pavement slab adjacent to the active gauges. This scheme worked well for measuring the load strains but was not as satisfactory for evaluating the temperature-related strains.

A typical instrumented jointed slab layout indicating the locations of the active gauges is shown in Figure 3. Other

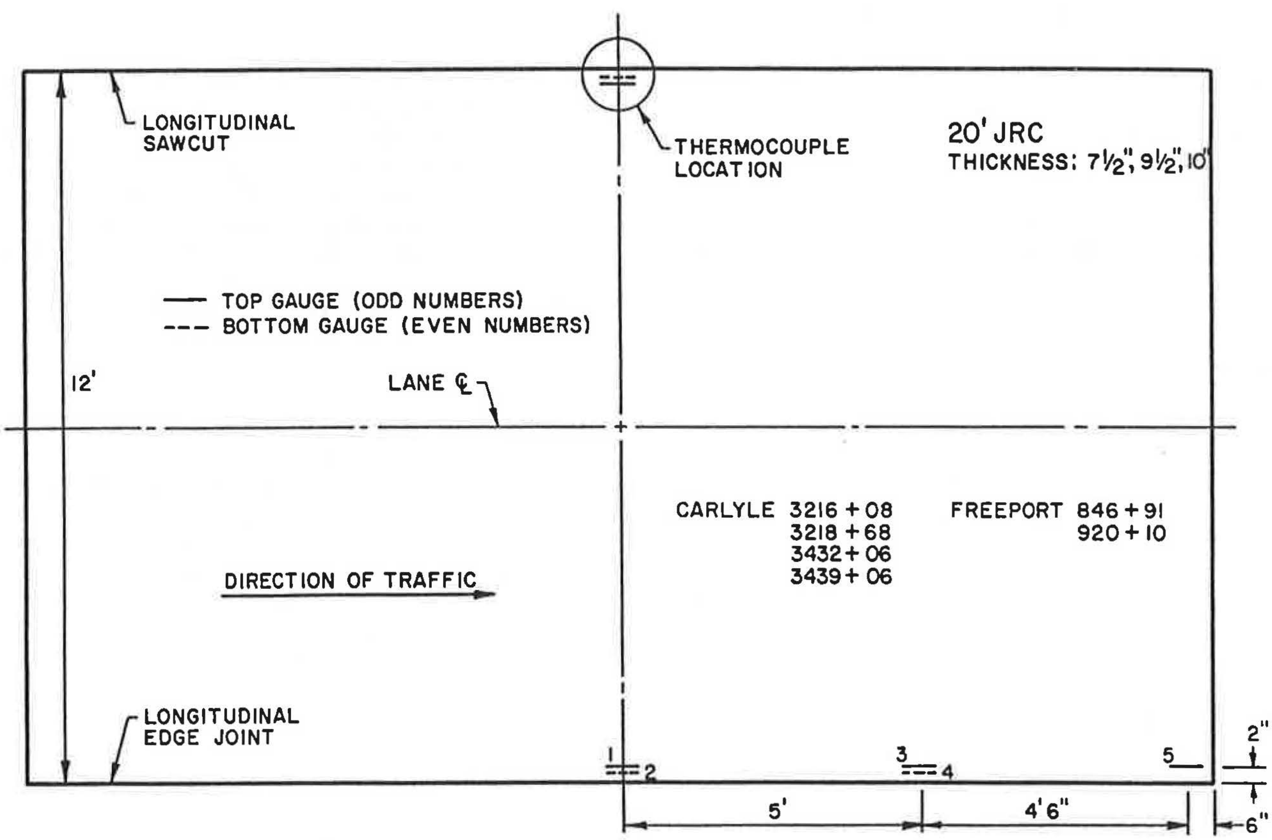

FIGURE 3 Instrumented slab layout.

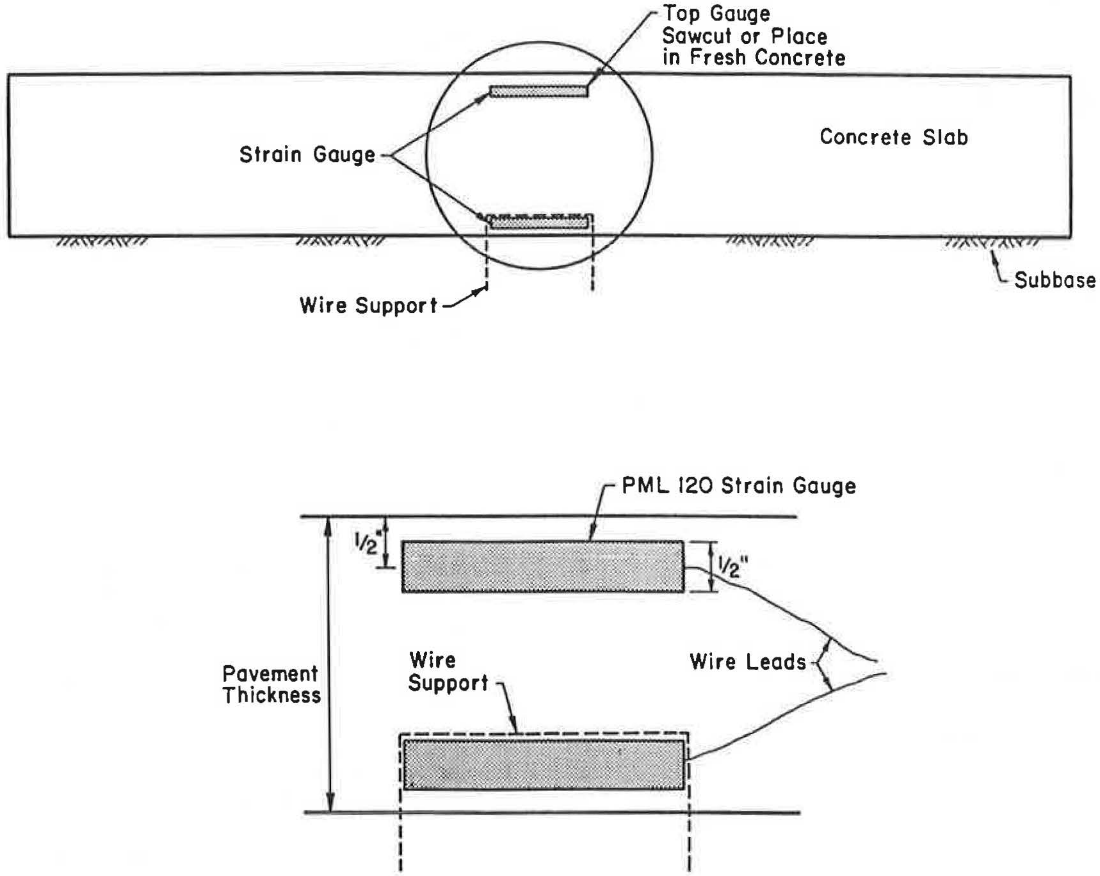

FIGURE 4 Strain gauge pavement installation.

similar joint spacing and gauge layout configurations were also included in the project instrumentation (*1*) but are not shown here. The gauges were strategically placed to measure the maximum strain caused by a wheel load placed at or near the pavement edge and the strain caused by slab curling. Gauges were generally placed in pairs along selected transverse and longitudinal joints with one gauge at the slab top and the other near the bottom. Gauges at the slab corners were reference gauges, so only the top gauge was installed at these locations.

Encapsulated gauges were also installed in several CRC pavements, but these are reported here only briefly for reference. The measured strains in the CRC pavements are reported elsewhere (*2*). Basically, the gauges in the CRC pavements were positioned to measure transverse and longitudinal strains in the concrete midway between the transverse cracks. Gauge installation procedures for the CRC pavements were essentially the same as those for the jointed pavements, except that all top gauges were installed using the saw-and-grout method discussed later. Strain gauges were also installed on several longitudinal steel bars in the CRC pavements. The gauges on the reinforcing bars were positioned so that strain gradients along a bar segment near and adjacent to transverse cracks could be established.

After the roadway had been graded and trimmed, but before the subbase (lean concrete) was placed, a 4-ft-deep trench was cut from beyond the outer edge of the shoulder to approximately the wheel path in the paving lane. A PVC conduit was installed in this trench, and lead wires from the dummy gauges and the gauges placed at the bottom of the pavement were routed through the conduit. Grooves were cut in the top of the subbase to run the lead wires from the individual gauges to the conduit inlet box. The lead wires were carefully marked to indicate the gauge and location and were run to an outlet box attached to a 4-by-4 post beyond the outer edge of the shoulder.

Accurate location of the gauges was considered to be essential if meaningful data were to be collected. As soon as the lean concrete subbase had cured, the proposed locations of the bottom gauges were marked on the subbase surface. A support system consisting of a thin metal rod bent into the shape of a U was installed in two holes drilled into the subbase, as shown in Figure 4. The gauges were then attached to the supports. Installation of the top gauges is discussed later.

During the paving operations, the contractor was requested to slow the paving speed and reduce the concrete head as the paver approached the instrumented sites. Approximately 5 min before the paver reached the instrumented site, plastic concrete was placed directly over and around each gauge to prevent movement of the gauges and tearing of the lead wires. This procedure appeared successful as no gauges were lost because of the paving operations.

An acceptable procedure for supporting the top gauges in the concrete was not found, so the gauges were installed in the concrete after the finishing operations were complete. Three different procedures were used for this installation.

The first method for installing the top gauges was to saw a groove in the hardened concrete and then to bond the gauges in place by using a sand cement grout. This procedure was effective but did not provide immediate readings of the strains. There was also some concern about the long-term effectiveness of the grout, which is essential for transferring the strains from the concrete to the gauges. All of the top gauges in the CRC pavements were installed in this manner.

A second method involved placing a wood plug in the fresh concrete at the approximate gauge location. As soon as the concrete had taken on a set, the plug was removed and the gauge was placed in the void. Again, the gauge was grouted into place by using a sand cement grout. Because it permitted earlier readings of the strains, this method was judged superior to the first method. The main problem with this approach was the concern about the long-term effectiveness of the grout.

The third procedure involved working the gauge into the fresh concrete and carefully compacting the fresh concrete around the gauge. The lead wires were also worked into a groove in the fresh concrete, which was cut with a trowel. This method alleviated the concerns over the grout effectiveness and permitted immediate readings of the strains. However, accurate placement (both alignment and depth) was more difficult to achieve with this procedure. With some practice, this would be the recommended procedure for any future installations.

STRAIN RECORDING

Strains are measured as voltage changes in the strain meters within the system. These voltage changes are then amplified, processed, displayed, and stored. For every gauge and every reading there must be a zero value and a calibration reading. Calibration readings were recorded with strain readings.

For static loading, the strains were read using a portable strain meter, and the data were recorded manually. For the dynamic loading, the readings were recorded on a recorder, capable of recording 10 channels of data simultaneously. These readings were recorded on tape and then transferred to floppy disks and read directly into a spread sheet using Lotus 1-2-3.

One of the most difficult tasks in collecting this type of data is to minimize unwanted electrical noise. Much of the noise comes from such sources as electrical high-tension wires near by, automobile ignition sparks, radio signals, and other sources. High-quality lead wires, connectors, and mating plugs were used to keep the noise to a minimum. However, the first attempt at recording the strains under dynamic loading still produced significant noise problems. Through careful grounding of the equipment and installation of high-frequency filters a significant amount of the noise was eliminated for the subsequent tests.

THERMOCOUPLES

Temperature changes in the concrete and temperature gradients through the slab can significantly affect the measured responses of PCC pavements. Thermocouples were installed near the top and bottom of several slabs within the test site. The thermocouples were installed near the pavement edge in CRC pavements and near a corner in the jointed pavements. The thermocouples were installed by fastening them to a polyester tube at the desired heights and fastening the tube to reinforcing bars in the pavements.

During the load testing procedures, the thermocouples were read directly with a potentiometer or a digital thermometer. For longer-term readings, that is, readings taken over 24-hr or longer periods, the temperature data were recorded on a multichannel, battery-powered portable recording system. The recording device was programmed to sample the data at preselected intervals throughout the test period. The device had a memory of 64K and, when the device was filled, the data were transferred directly to floppy disks using a portable IBM-compatible computer system.

MATERIALS

Subgrade Soils

Soils at the test site near Carlyle in southern Illinois were mainly glacial till, overlain with a relatively thin layer of wind-deposited loess. The soil types ranged from silt loam to clays, with the predominant soil type a silty clay.

The soil at the test site near Freeport in northern Illinois was also glacial till and was classified as a silt loam with an AASHTO classification of A-4(8), with poor drainage characteristics. Soil support at this site was non-uniform, because there were a number of rock outcroppings within the test site.

Plate load tests were conducted at each site after the final grading but before placing the subbase. The tests were run at random locations throughout the project sites. The k values obtained from the plate load tests for both sites are given in Table 2.

Falling weight deflectomer (FWD) tests were run on the top of the subgrade to obtain dynamic k values. A 30-in.-diameter plate was placed on the subgrade, and the FWD test was run on top of the plate. Dynamic tests were run only at the Carlyle site. These results are also shown in Table 2 along with a ratio of the dynamic to the static k values. The average ratio of dynamic to static k is 1.30, with a standard error of 0.26.

Subbase

The subbase for both projects was lean concrete with a compressive strength of approximately 2,500 psi after 1 year of service. In Illinois this material is commonly referred to as "econocrete." The econocrete was placed with a concrete paver to a depth of 4 in. and finished with a float, and a coat of liquid curing compound was applied. The specifications called for the subbase to cure for 7 days before placing the concrete.

Concrete

Concrete used in both test projects met the Illinois Department of Transportation (IDOT) standards for paving class concrete. The IDOT standards call for a mix with a 14-day strength of 650 psi, when tested in flexure under center point loading.

TABLE 2 SUMMARY OF PLATE LOAD TEST RESULTS

	Project 409 Carlyle, IL			Project 401 Freeport, IL
	Static k psi	Dynamic k psi	Ratio Dynamic k/Static k	psi
	116	120	1.03	529
	119	202	1.70	412
	50	145	2.90	360
	174	194	1.12	527
	86	128	1.49	248
	210	129	0.64	282
	143	119	0.83	312
	169	124	0.73	345
Avg.	133	145	1.30	377
std dev	51	34	.74	105

Sufficient beam specimens were cast from the concrete used in the instrumented slabs so that 14-, 28-, and 90-day strengths could be determined. The beams tested to measure the 28- and 90-day strengths were stored on the project sites. The beams were wrapped in plastic sheets to prevent drying, buried in a pit alongside the pavement, and covered with moist sand. Thus, the beams were cured until testing under conditions comparable to the concrete in the pavement. Maturity meters were also installed at project sites to monitor the concrete strength development before loading and testing.

Table 3 shows a summary of the 28-day concrete properties for the Carlyle project. The effective modulus of rupture under third point loading was 713 psi, with a compressive strength of 5,332 psi. The modulus of elasticity measured during compressive testing was 4.16 × 10 psi. The variability in the concrete properties was very low, with the coefficient of variation under 10 percent for both the compression and flexure test results.

TABLE 3 28-DAY CONCRETE FLEXURAL AND COMPRESSIVE STRENGTH AT CARLYLE, ILL.

Station	Flexural Strength Center Point*	Third Point**	Compressive Strength*	E x 10⁶
·3216+12	989	840	6084	4.43
3229+87	802	682	4651	3.88
3262+50	856	728	5736	4.32
3275+00	840	714	--	--
3352+50	-	-	5335	4.16
3395+00	-	-	5229	4.12
3432+50	750	638	--	--
3505+00	827	703	4994	4.03
3510+00	806	685	--	--
Average	838	713	5332	4.16
STD DEV	74	63	502	.20
Coef of Var (%)	8.8	8.8	9.4	5.72

* Measured Value
** Calculated Value at 85% of Center Point Load

TYPICAL TEST RESULTS

Pavements at both sites were tested under both static and moving truck axle loads. The primary load system was a single-axle truck with 18 kips on the rear axle. Initial tests on the pavements at Carlyle were during July 1986, approximately 30 days after placing the concrete for the mainline pavement slabs, and before the tied concrete shoulders were added. These same pavements were retested during the summer of 1986, after the shoulders had been added and the pavements had been open to traffic. Pavements at the Freeport site were tested initially during the fall of 1986, both with and without tied shoulders similar to the tests at Carlyle.

Pavements at both sites have subsequently been tested under similar loading conditions, in both the summer of 1987 and the late spring of 1988. In all, a total of over one hundred 360K capacity floppy disks have been filled with data. Since most of the gauges installed are still active and in good working order, it is anticipated that subsequent testing will be done on these sites.

Since the primary focus of the testing for this project was to validate the ILLI-SLAB model to predict pavement response to load, sufficient data were reduced as soon as possible to verify this for several different pavement configurations and loading conditions. Examples of results obtained are presented herein. However, much of the data have not yet been reduced, and work is continuing on this phase of the study. More complete results will be presented in the literature over the next few years.

Jointed Concrete Pavements

Figure 5 shows some typical comparisons obtained between the calculated and measured strains in jointed concrete pavements. The maximum strains were recorded by gauges installed near the edge of the slab at a point midway between transverse joints (gauges 1 and 2, Figure 3), with a static wheel load placed directly over the gauge. Variation in strains at the midslab position (gauges 1 and 2) as the load was moved away from the gauge location is also shown in Figure 5. The appar-

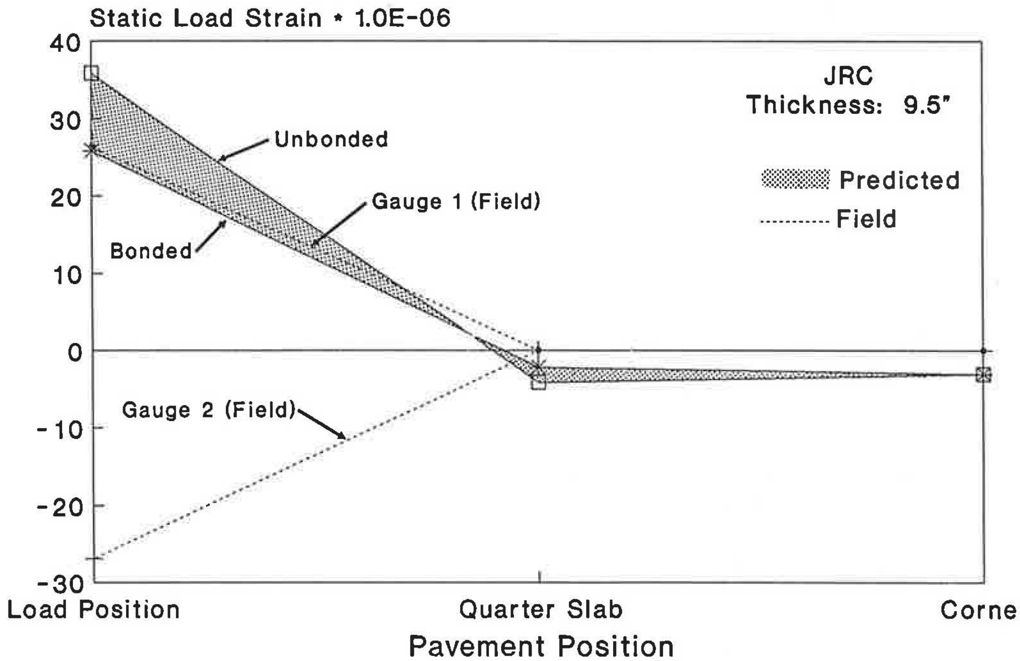

FIGURE 5 Typical results from measured strains under load from Illinois HPR projects 401 and 409.

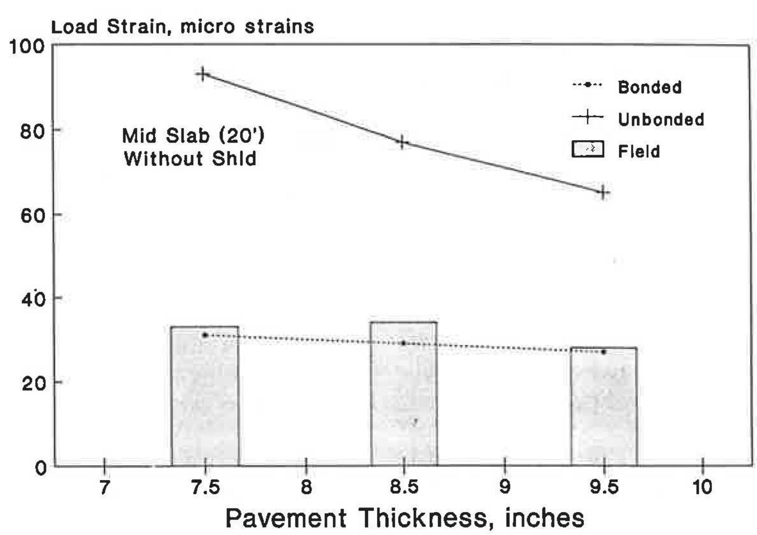

FIGURE 6 Load strain at midslab without tied PCC shoulder [18-kip single-axle load (SAL)].

ent "mirror image" strains (+ and −) are from gauges at the top and bottom of the slab.

One of the more interesting aspects of these data is the effect of bond between the slab and the subbase. The theoretical results are shown for both the bonded and unbonded conditions based on ILLI-SLAB analyses (*3*). The measured strains suggest that there was significant bonding between the slab and subbase when these tests were conducted. Tests conducted in the late spring of 1988 indicate that this bond may be breaking down.

Since the gauges away from the immediate loaded area show small strains, the remainder of the data presented herein for the jointed pavements is from midslab gauges only.

Figure 6 shows measured and calculated strains from a series of slabs 7.5, 8.0, and 9.5 in. thick. In these data the measured strains are in good agreement with the calculated values for the bonded condition, but the calculated strains for the unbonded condition are significantly greater than those for the bonded condition.

Figure 7 shows the effect of speed on the measured strains in the pavements. Again, the measured and theoretical results for the bonded case are in good agreement, but the theoretical results for the unbonded condition are significantly higher.

The effects of tied PCC shoulders on the strains in the jointed pavements are shown in Figure 8. The trends with regard to speed and bonding to the subbase are the same as those shown for the slabs without shoulders (Figures 6 and 7). The results clearly show the benefits of tied shoulders in reducing edge strains in jointed PCC pavements.

Temperature Strains

Temperature gradients were recorded for both the jointed and CRC pavements. Figure 9 shows the gradients in a jointed pavement for the winter of 1986 and the spring of 1987, along with the gradients and percent time assigned for the gradients in the design procedure for jointed concrete pavements. Table 4 gives a summary for the gradients at various times for both sites.

Results from measured strains caused by curl are somewhat more difficult to interpret. If, for example, a slab is fully restrained, and if the thermal expansion of the gauge and the concrete are the same, then there should be no measured strains in the slab caused by curl. Conversely, if a slab is completely unrestrained, then the measured strains caused by curl should be equal to the thermal strain differential between the top and bottom of the slab, but there would be no curl stress. The actual situation is somewhere between these two extremes; the only way to get an estimate of the curl strains is to have one gauge located in a position where one would not expect any curl restraint, and to evaluate the difference between the restrained and unrestrained gauge readings.

Using the strain difference technique, the strains in a typical jointed concrete at Carlyle were determined and are shown in Figure 10. The measured strains show good agreement with the theoretical strains for curl in these pavements. The theoretical strains were determined by using an algorithm developed from a series of runs with the ILLI-SLAB program, with the weight of the slab as the restraint.

TABLE 4 THERMAL GRADIENT DURATION PERIODS

Location	Station	Thickness	Season	Thermal Gradient Positive	Thermal Gradient Negative	Zero
Carlyle	3432+06	7-1/2"	Summer 86	28%	47%	25%
			Fall 86	10%	71%	19%
			Winter 86	5%	78%	17%
			Spring 87	46%	27%	27%
			Average	22%	56%	22%
	3218+68	9-1/2"	Summer 86	36%	57%	7%
			Fall 86	9%	84%	7%
			Winter 86	8%	67%	25%
			Spring 87	52%	40%	8%
			Average	26%	62%	12%
Freeport	937+30	10"	Summer 86			
			Fall 86	12%	26%	62%
			Winter 86	18%	35%	47%
			Spring 87	25%	43%	32%
			Average	18%	35%	47%
		Overall Average		22%	51%	27%

SUMMARY

Instrumented pavement sections are a powerful tool for validating mathematical models used to predict the basic response of pavements. Throughout this paper the results, both measured and calculated, have been given as strains. Strains are a basic pavement response that can be measured, as compared with stresses, which are fictitious values that can be calculated only if a value is assumed for the *E* of the material being tested. Measured strains are real physical properties and can be considered basic pavement responses.

Results obtained from these tests indicate that the models used in the pavement analysis provide an accurate response of the pavement to both load and environmental conditions, provided the appropriate conditions are used in the analyses. Bonding of the slab to the subbase can, for example, have a significant impact on the results. For design, one can always assume the worst condition, and, if the other condition happens, there is a greater factor of safety in the design. When evaluating the accuracy of the models, however, it is vital that one know the true condition of the pavement, or, as shown in the paper, some of the results will be different than is expected.

Results from the instrumented pavements verify that climatic conditions have a profound effect on the behavior of PCC pavements. For jointed PCC pavements the combined curl and warping strains can be as large or larger than the anticipated load strains.

For CRC pavements, the total changes from the temperature at which the slab was cast have a profound impact on

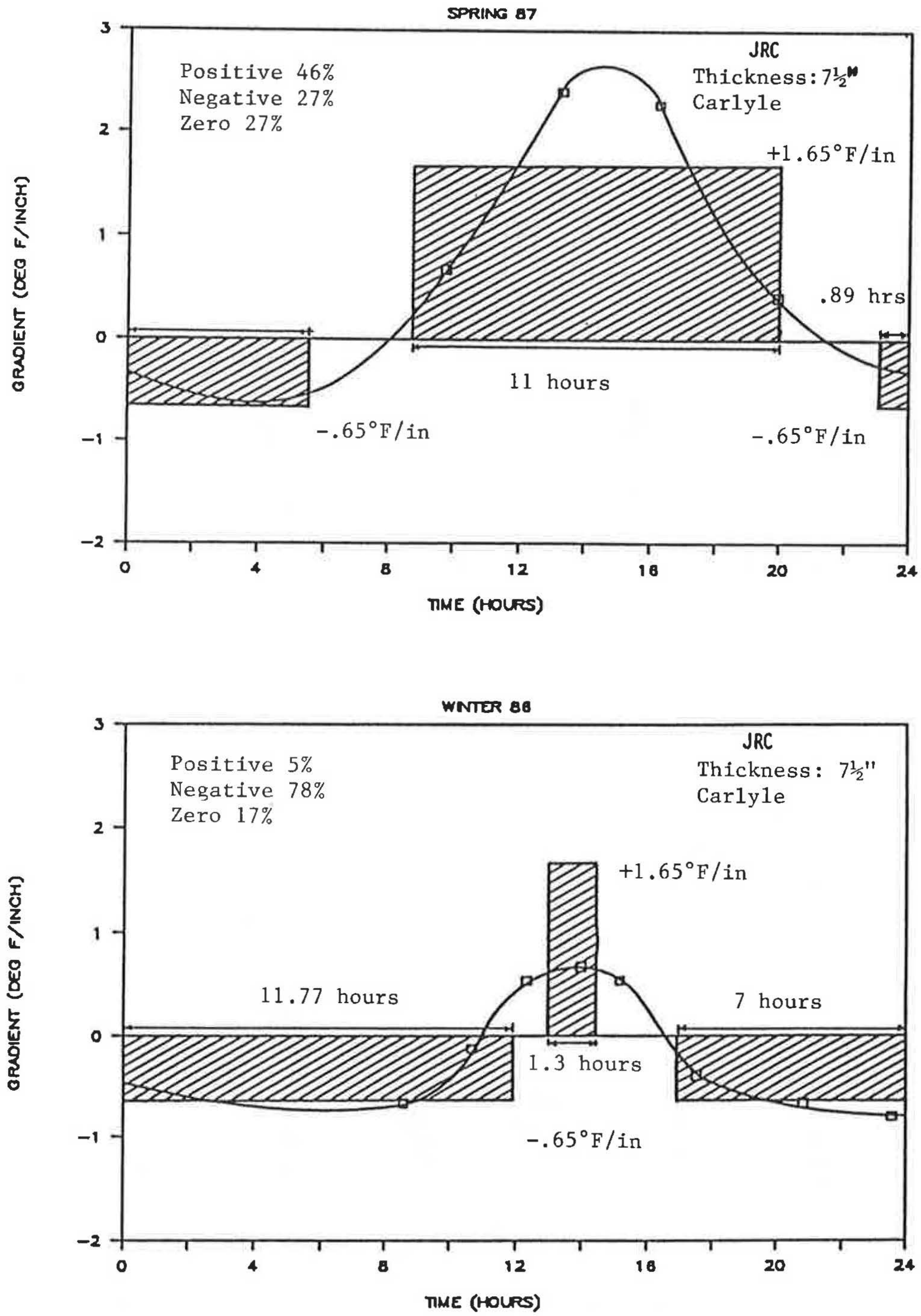

FIGURE 9 Seasonal pavement temperature gradients with equivalent time versus gradient diagrams (spring 1987 and winter 1986).

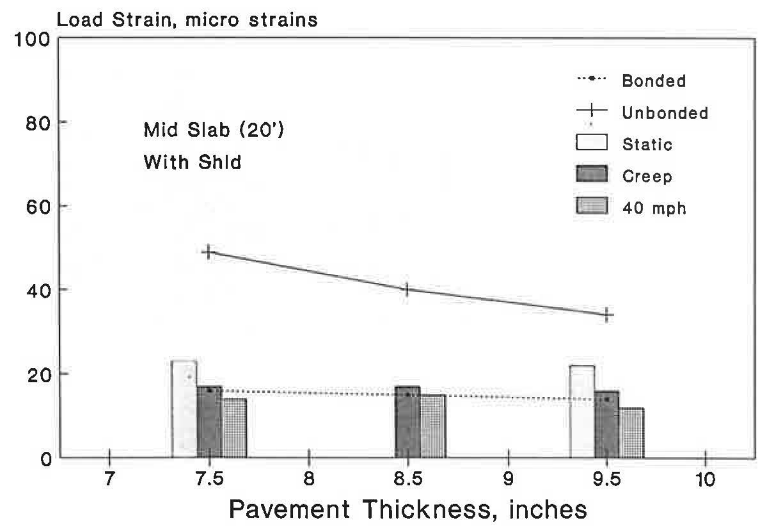

FIGURE 7 Load strain at midslab with tied PCC shoulder (18-kip SAL).

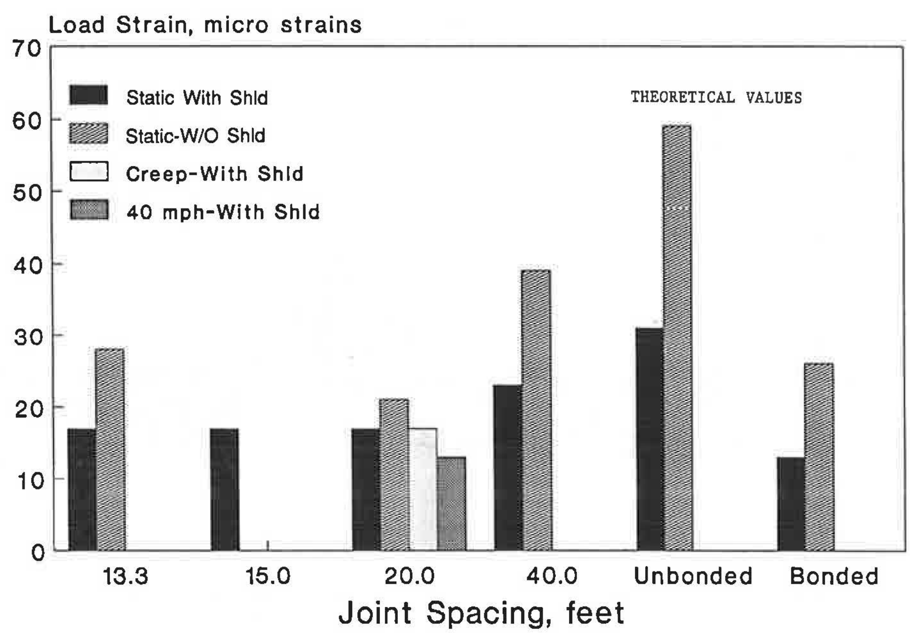

FIGURE 8 Comparison of load-induced strain at various joint spacings (static and dynamic strains).