2005-47

Final Report

LOAD TESTING OF INSTRUMENTED PAVEMENT SECTIONS

Minnesota Department of Transportation

Research

Technical Report Documentation Page

1. Report No. MN/RC-2005-47	2.	3. Recipients Accession No.

4. Title and Subtitle LOAD TESTING OF INSTRUMENTED PAVEMENT SECTIONS	5. Report Date November 2005 6.
7. Author(s) Erland O. Lukanen, P.E.	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Minnesota Department of Civil Engineering 500 Pillsbury Drive SE Minneapolis, MN 55455	10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (c) 73590 (wo)185
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services Section 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
http://www.lrrb.org/pdf/200547.pdf

16. Abstract (Limit: 200 words)

This report summarizes and references seven previously written reports developed from this project. The objective of this project was to use the field-measured strains from a number of MnROAD cells to develop mechanistically based load equivalency factors (LEF). The load equivalency factors commonly in use were developed from the AASHTO Road Test conducted in the late 1950s at Ottawa, Illinois. The AASHTO-based LEF represented the pavement behavior at the Road Test and might not reflect conditions in other climates, other subgrade soils, pavement sections, traffic and so on. Several of the MnROAD project objectives related to the development of improved mechanistic models and the development of improved pavement design methods.

The Load Testing of Instrumented Pavement Sections project included strain measurements from a variety of vehicle loads, including single, tandem, and tridem axles, tire pressures, tire types, various vehicle speeds, and several different seasons. The testing and analysis resulted in the evaluation of various mechanistic models and the selection of WESLEA for flexible pavements and ISLAB2000 for rigid pavements. Many of the strain sensors, installed during construction in 1993 or 1994, no longer worked limiting the number of test cells available and the scope of the study. The LEF analysis for flexible pavements were based on only the tensile strain at the bottom of the asphalt, and were generally lower than the corresponding AASHTO factors. There were too few strain sensors available to conduct an LEF analysis on rigid pavements, however, during the selection of ISLAB2000, a number of relationships were developed that relate k-value, to other factors such as slab thickness, slab elastic modulus, and strain.

17. Document Analysis/Descriptors Pavement response Load equivalency factors Pavement Strain	Mechanistic models	18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 24	22. Price

LOAD TESTING OF INSTRUMENTED PAVEMENT SECTIONS

Final Report

Prepared by:
Erland Lukanen
University of Minnesota
Department of Civil Engineering
500 Pillsbury Avenue
Minneapolis, MN 55455

November 2005

Published by:
Minnesota Department of Transportation
Research Services Section
395 John Ireland Boulevard, MS 330
St. Paul, MN 55155

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INTRODUCTION

This project, *Load Testing of Instrumented Pavement Sections*, was conducted to learn more about pavement response to vehicle loads. MnROAD was constructed with 40 test cells including both rigid and flexible designs. Many of the test cells were heavily instrumented to allow the measurement of critical pavements responses to vehicle loads. The instrumentation also included sensors to monitor the subsurface temperatures, moisture, and frost activity. Several types of vehicles were used to load the pavements:

- 5-axle tractor semi-trailer truck
- 6-axle tractor semi-trailer truck (tridem on trailer)
- 2-axle transit bus
- Passenger car

Each of these vehicles, except the passenger car, was run at several loads. Additional test variables included vehicle speed, tire pressure, and tire type. Additional relevant data collected included the date and time of each vehicle pass, pavement temperature, and lateral position of the vehicle.

A detailed test plan was prepared where specific MnROAD sections were selected for load testing based on available instrumentation and pavement features. Adjustments in the detailed test plan were made during the field testing part of the project to deal with items such as failed sensors, sensor responses, and equipment availability.

Much of the work following the field data collection was directed toward comparison of the measured strains with those predicted by various pavement response models, including elastic layered models for flexible pavements and dense liquid foundations models, elastic layered foundation models and finite element (F-E) models for rigid pavements. The results of that work then allowed some comparison of the strains that develop from various loading configurations and conditions. Part of the initial concept for this project was to develop load equivalency factors similar to those developed from the AASHTO Road Test experiment where any axle combination and load can be converted into the equivalent number of passes of an 18,000 pound single dual-tired axle. The AASHTO equivalency factors, however, reflect all conditions that can change serviceability, including rutting, faulting, ride, etc. and the measurements made at

MnROAD only address tensile strains and the possible effects tensile strains might have on pavement performance.

The research results, therefore, are very valuable for the calibration of mechanistic-based pavement design. The goal of mechanistic pavement design is to develop a more direct connection between various modes of pavement deterioration, such as fatigue cracking, and the strains from repeated truck loadings. The strains measured at MnROAD can be and have been used in the calibration of the mechanistic load response models used in mechanistic design programs such as MnPAVE and the NCHRP 1-37A Mechanistic-Empirical Pavement Design Guide.

Project Overview

Objectives

This project was developed primarily to investigate load equivalency factors for the various conditions represented by MnROAD, plus variations in traffic. The stated project objectives described in the Detailed Work Plan are shown in Figure 1.

> *One of the primary objectives of this study is to evaluate the accuracy and reliability of existing methods for determining primary pavement response LEFs and to develop and/or validate a more rational and mechanistic-based pavement response and performance approach. Another primary objective of this study is to investigate how each method accounts for parameters such as axle load, axle configurations, gross vehicle load, tire pressure, pavement structure, material properties, environmental conditions, and other quantifiable factors.*

Figure 1. Stated Project Objectives from the Detailed Work Plan.

The tasks identified to accomplish the project objectives are listed in Table 1. The project resulted in seven stand-alone reports, plus this final summary report.

Two of the reports correspond to Tasks A and B as shown in Table 1. Four reports correspond to Tasks C through F. Task G was added to the study to further evaluate mechanistic load response models for rigid pavements, and resulted in a stand-alone report. This report is the Final Summary Report for Task H.

Funding for this project came from the Minnesota Department of Transportation and the Pooled Fund program as project SPR-2(179). The Pooled Fund partners include fifteen states, California, Florida, Iowa, Idaho, Illinois, Kansas, Minnesota, North Dakota, Nebraska, New Jersey, New York, Ohio, South Carolina, Texas, and Washington.

Table 1. Stand-Alone Report from this Project.

Task	Title	Author(s)	Dated
A	Literature Review[1]	Univ. of Minnesota	Feb 1999
B	Field Data Collection Work Plan[2]	Glasgow, Forst, Koubaa, Snyder	May 1999
C – F	Load Equivalency Factors from the Structural Response of Flexible Pavements[3]	Angel Mateos Moreno	June 2000
C – F	Calibration of Rigid Pavement Structural Model using Mn/ROAD Field Data[4]	Jesse J. Forst	Dec 1998
C – F	Calibration of Flexible Pavement Structural Model using Mn/ROAD Field Data[5]	Wenjin Bao	Dec 2000
C – F	Load Equivalency Factors from the Structural Response of Rigid Pavements[6]	Matt Oman	Sep 2005
H	Final Summary Report	Univ. of Minnesota	Sep 2005
G	Improved Techniques for applying the Finite Element Method to Strain Prediction in PCC Pavement Structures[7]	Drexel M. Glasgow	June 2001

MnROAD Facility

MnROAD is an outdoor pavement research facility located on Interstate Highway 94 in Ostego Township between Albertville and Monticello, Minnesota (about 40 miles northwest of Minneapolis). Construction of the test cells took place in 1992 and 1993 and the test cells were opened to traffic in August 1994. MnROAD consists of a mainline section that is a 3.5 mile (5.6 km) roadway that carries westbound Interstate 94 traffic that now averages about 26, 400 vehicles a day. It also includes a low-volume roadway, which is a 2.5 mile (4.0 km) closed loop that is trafficked by dedicated 5-axle tractor-semi-trailer trucks.

Construction of the MnROAD facility began in 1989 and was completed in 1994 when it was opened to traffic. The picture in Figure 2 shows most of the MnROAD facility. The direction into the picture is northwest. A black line in the picture crosses (from left to right) a railroad, the in-service eastbound I-94 roadway, the original westbound I-94 roadway, the MnROAD Mainline roadway that is trafficked by westbound I-94 traffic, and the two roadways of the low-volume loop. The ponds in each of the loops help maintain the water table at a high enough level to promote frost heave during the winter.

MnROAD was originally constructed with 40 test cells, 23 on the main line and 17 on the low-volume loop. A more detailed layout and composition of the test cells is available at the MnROAD web site[8]. MnROAD was heavily instrumented with sensors installed to measure stress, strain, and applied loadings. There are weigh-in-motion devices on the mainline. Environmental sensors include subsurface temperature sensors, moisture sensors, thermal strain sensors in the concrete, and frost detection devices. There are two on-site weather stations to measure temperature, dew point, precipitation, wind, and solar insolation.

Figure 2. MnROAD

The performance of the test cells is regularly monitored by recording surface distresses, longitudinal profile, transverse profile, and joint faulting. In addition, falling weight deflectometer measurements are periodically made and data is continually recorded from the environmental sensors.

LOAD TESTING OF MNROAD CELLS

The project included field testing with various vehicles and configurations. The first round of testing for the flexible pavements was conducted during 1997 using the MnROAD 5-axle tractor semi-trailer truck. The 1997 testing was a pilot study for the field loadings and used only the MnROAD truck at different loadings, tire pressures, and speeds [Bao]. The pilot testing for the flexible sections was conducted in the summer of 1997 and the rigid section pilot testing was conducted in the late fall of 1997. The second round of testing was conducted during the spring of 1999 and included multiple vehicles, axle configurations, and other loading parameters [Forst, Oman]. Figure 3 shows the flexible cells that were initially identified for use in the study work plan, the cells used in the pilot study, and the cells available for the load-equivalency factor analysis. Figure 4 shows the rigid cells that were initially identified for use in the study by the work plan, the cells used by Forst in the pilot study, and the cells available for Oman to use for the load equivalency factor analysis.

		Work Plan							Pilot Project - Bao						LEF
										Effects					
	Cell	SN	F-D vs Conv.	F-D Thickness	Drainable Base - PSAB	Subgrade Support	Base & Subbase Properties	Marshall Compction	WESLEA Validation	Strain[a]	Axle Load	Speed	Tire Pressure	Offset	Moreno
5 Year	1														
	2														
	3	X							X						
	4														
10-Year	14														
	15		X	X					X				X		
	16		X		X			X	X	T	X				X
	17								X		X	X	X	X	
	18								X			X			
	19							X							X
	20								X			X			
	21	X			X				X			X			
	22				X				X	T					
	23				X				X						
LVR	24														
	25					X			X				X		
	26			X		X			X	T&L				X	X
	27														
	28														
	29	X							X						
	30						X		X	T					X
	31						X		X						

[a] Direction of strain measurement designated by T or L for (T)ransverse and (L)ongitudinal.

Figure 3. MnROAD flexible cells used.

		Work Plan								Forst			Oman
	Cell	Jt Spacing	SG Moisture	Sublayer Thickness	PCC Thickness	Dowel - Undoweled	Jt Spacing - Base thickness & Properties	Dowel Diameter & Jt. Spacing	PCC Shoulders	Axle Loads[a]	Tire Pressure	Speed	Strain Database
5-Year	5												
	6			X	X		X		X	3	X		X
	7	X					X		X	2	X		X
	8												
	9	X		X					X	2	X	X	X
10-Year	10												
	11							X		2	X	X	X
	12												
	13							X		3	X		X
LVR	36		X			X					X	X	X
	37					X					X	X	X
	38		X		X						X	X	X
	39												
	40												

[a] Number of load levels used.

Figure 4. MnROAD rigid cells used.

The work plan for both the rigid and flexible and rigid cells included pavement design factors that could be evaluated as to their influence on load equivalency factors. In addition, factors such as vehicle load, axle configuration, tire type, tire pressure, and vehicle speed were included as part of the test plan.

Vehicle parameters recorded during the field testing included items such as axle configuration and loads, tire pressures, vehicle speed, and offset from the edge of the pavement. Environmental conditions, both atmospheric and subsurface, were monitored during testing. Pavement structural configurations were available from other reports. The embedment strain sensors included in the flexible pilot study included longitudinal strain gauges and transverse strain gauges, both at the bottom of the asphalt. The embedment strain sensors in the rigid pavements included strain sensors placed at nominal distances of one inch from the top and from the bottom of the slab.

During the pilot study testing in 1997, it was found that a number of sensors were no longer working [Bao and Forst], and the actual position and gauge orientation varied from planned[9]. By the time the 1999 testing was conducted, only a few cells had strain gauges that provided meaningful information.

New strain sensors were retrofitted on some of the rigid cells [Oman] that did not have functioning strain gauges. Retrofitted strain gauges were also installed adjacent several existing strain gauges for comparison. The retrofitted sensors were found to provide results that were consistent with the original sensors.

Mechanistic Load Response Models

Three reports from this study relate to the evaluation and adaptation of mechanistic load response models. These reports compared the strains predicted by available mechanistic models to the measured field responses at MnROAD during the pilot testing in 1997. Bao selected and evaluated an elastic layered mechanistic model and a finite element model available for flexible pavements, and Forst evaluated JSLAB-92, a finite element model for rigid pavements. Glasgow evaluated a newly available ISLAB2000 finite element model for rigid pavements.

Mechanistic Models for Flexible Pavements

The models evaluated for flexible pavements by Bao including WESLEA and ILLI-PAVE. WESLEA is a linear elastic layered program that was developed by the U.S. Army Corps of Engineers for pavement analysis, and ILLI-PAVE is a finite element program developed at the University of Illinois for flexible pavement analysis. Bao found the two programs provided reasonably equivalent results. WESLEA was selected because of its operational advantages; it was easier to use and offered more utility as an analysis program. Bao used WESLEA to predict the horizontal strains at the bottom of the asphalt to compare with the strains that were measured at MnROAD during the summer of 1997. The predicted strains were compared to the measured strains and ratios of measured-to-predicted strains were calculated.

Calibration of the predicted WESLEA strains to measured strains was done for a number of factors such as axle loads, tire pressure, vehicle offset position, and the thickness of asphalt layer (TAC). Bao concluded that the trend of the ratios of predicted strains from

WESLEA to measured field strains was close to one for the factors evaluated, except for the strains relating to vehicle speed, which varied significantly due to viscoelastic effects. Relationships were developed to calibrate the WESLEA-predicted strains to those measured in the field. Figure 5 is a figure extracted from Bao's report that compares the calibrated WESLEA-predicted strains to those measured in the field for all of the cells measured.

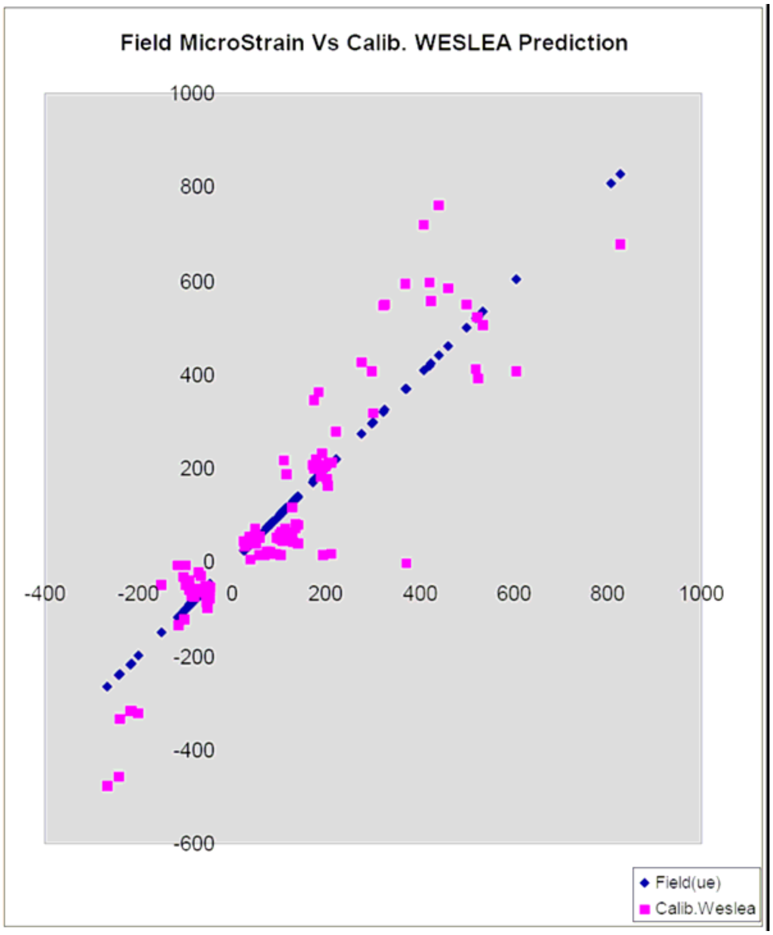
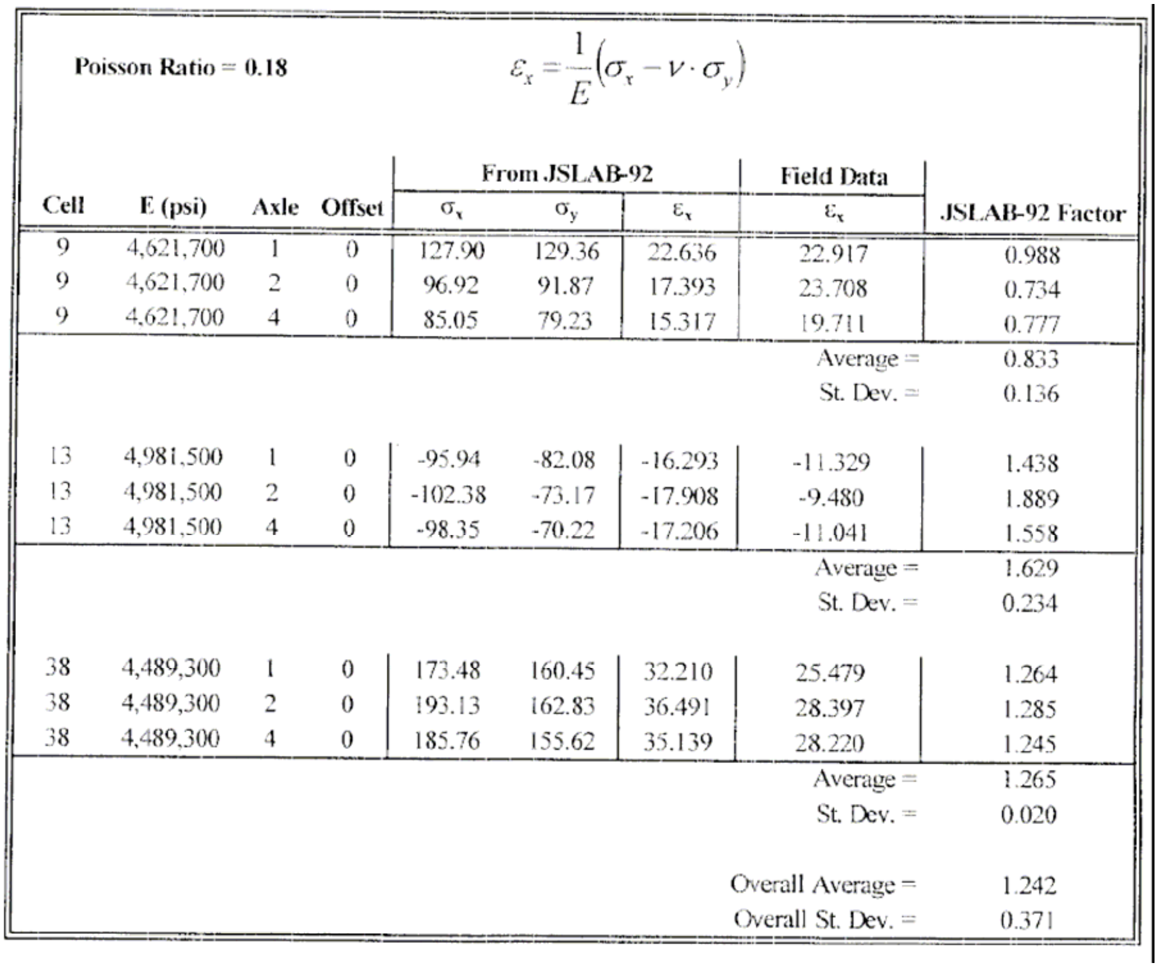


Figure 5. Figure 4.18 from Bao's report comparing predicted to measured strains.

Mechanistic Models for Rigid Pavements

The field test results from the rigid pavement pilot study was analyzed by Forst using JSLAB-92, a finite element program developed for concrete pavements. The embedded strain sensors were typically one inch from the top and bottom of the slab, so Forst develop procedures to adjust the measured strains to represent the strains at the top and bottom of the slab. He then developed a means of adjusting for the vehicle lateral position. The final adjustment process developed was a procedure to adjust the mid-slab strains to represent the critical strain positions at the pavement bottom edge. Forst concluded that the field test results were erratic and clear trends were difficult to identify, as indicated by Table 4.9 of his report, also shown here in Figure 6. Also, JSLAB-92 predicted strains averaged 74 percent more than the measured dynamic field strains.



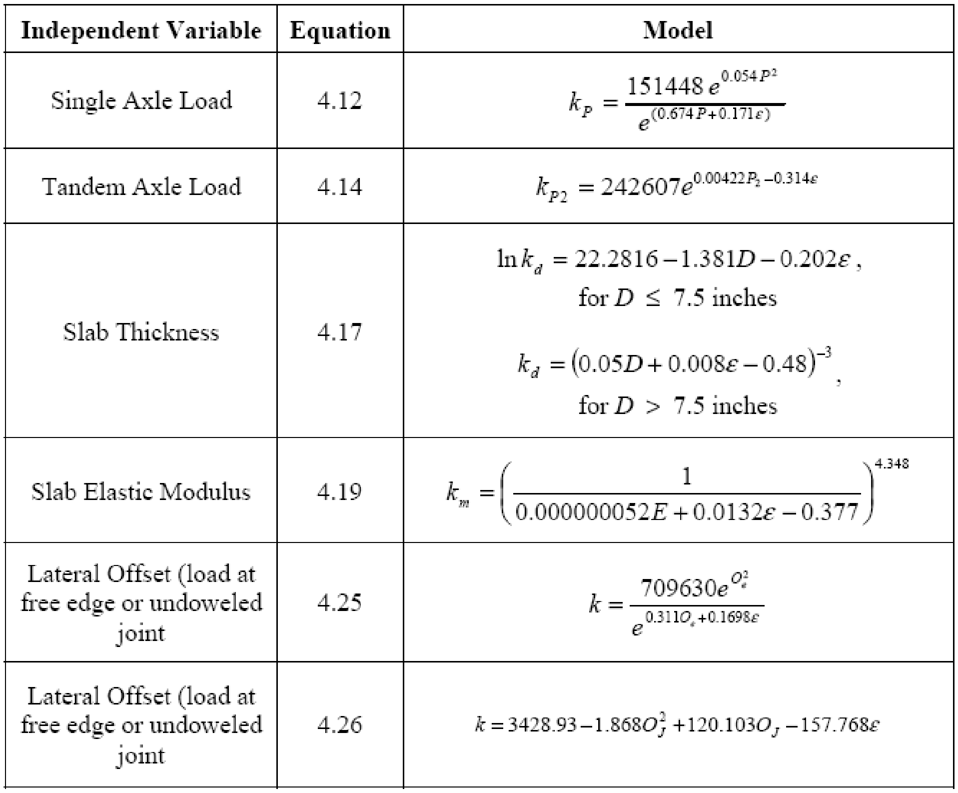
Poisson Ratio = 0.18

$$\varepsilon_x = \frac{1}{E}\left(\sigma_x - \nu \cdot \sigma_y\right)$$

Cell	E (psi)	Axle	Offset	From JSLAB-92			Field Data	JSLAB-92 Factor
				σ_x	σ_y	ε_x	ε_x	
9	4,621,700	1	0	127.90	129.36	22.636	22.917	0.988
9	4,621,700	2	0	96.92	91.87	17.393	23.708	0.734
9	4,621,700	4	0	85.05	79.23	15.317	19.711	0.777
							Average =	0.833
							St. Dev. =	0.136
13	4,981,500	1	0	-95.94	-82.08	-16.293	-11.329	1.438
13	4,981,500	2	0	-102.38	-73.17	-17.908	-9.480	1.889
13	4,981,500	4	0	-98.35	-70.22	-17.206	-11.041	1.558
							Average =	1.629
							St. Dev. =	0.234
38	4,489,300	1	0	173.48	160.45	32.210	25.479	1.264
38	4,489,300	2	0	193.13	162.83	36.491	28.397	1.285
38	4,489,300	4	0	185.76	155.62	35.139	28.220	1.245
							Average =	1.265
							St. Dev. =	0.020
							Overall Average =	1.242
							Overall St. Dev. =	0.371

Figure 6. Table 4.9 from Forst Report comparing predicted to measured strains.

Because of the disappointment in the ability to match predicted strains to measured strains as reported by Forst, Task H, an additional task, was added to the project to evaluate mechanistic models for rigid pavements. In this task, Glasgow evaluated several finite element models (FEM) including ILLI-SLAB, EVERFE and ISLAB2000. Glasgow conducted a large number of FEM runs with ISLAB2000, using the results to compare to the measured field strain values. Glasgow concluded that the subgrade support k-value was not constant for a given soil, but varied by how it is loaded. Using this approach, he developed a process of calculating a 'dynamic' k-value. Using the "dynamic" k-values, the predicted strains more closely matched the measured strains. Using the results, Glasgow produced a number of equations that related the measured strain and another parameter, such as slab thickness, slab modulus, wheel load, and so on, to k-value. The resulting equations are contained in Table 5.1 of Glasgow's report, as shown in Figure 7. For example, Glasgow developed regression equation 4.12 to predict the k-value from the load on a single axle and the measured strain. He also developed similar equations for tandem axles, slab thickness, slab elastic modulus, and lateral offset. For the regression equations developed, Glasgow concluded that the measured strain and slab modulus did the best job in predicting the field k-value as determined from backcalculation of falling weight deflectometer test data.



Independent Variable	Equation	Model
Single Axle Load	4.12	$k_P = \dfrac{151448\, e^{0.054 P^2}}{e^{(0.674 P + 0.171 \varepsilon)}}$
Tandem Axle Load	4.14	$k_{P2} = 242607 e^{0.00422 P_2 - 0.314 \varepsilon}$
Slab Thickness	4.17	$\ln k_d = 22.2816 - 1.381 D - 0.202 \varepsilon$, for $D \le 7.5$ inches $k_d = (0.05 D + 0.008 \varepsilon - 0.48)^{-3}$, for $D > 7.5$ inches
Slab Elastic Modulus	4.19	$k_m = \left(\dfrac{1}{0.000000052 E + 0.0132 \varepsilon - 0.377} \right)^{4.348}$
Lateral Offset (load at free edge or undoweled joint	4.25	$k = \dfrac{709630 e^{O_e^2}}{e^{0.311 O_e + 0.1698 \varepsilon}}$
Lateral Offset (load at free edge or undoweled joint	4.26	$k = 3428.93 - 1.868 O_J^2 + 120.103 O_J - 157.768 \varepsilon$

Figure 7. Dynamic k-value models as shown in Table 5.1 of Glasgow's report.

Load Equivalency Factors

Flexible Pavements

The testing and analysis for load-equivalency factors was conducted following the pilot studies. The field testing was conducted during the spring of 1999 for the flexible sections. The field testing included several vehicle types with single steering axles, tandem axles, and tridem axles. The field testing also included multiple speeds and several tire types and pressures.

The flexible pavement study concentrated on the tensile strains at the bottom of the asphalt. It was noted that the currently used load equivalency factors developed from the AASHTO Road Test are performance based and represent all factors that affect serviceability, including change in ride, rutting, and cracking and patching. Tensile strains at the bottom of the asphalt are thought to mainly relate to fatigue (alligator) cracking, so this study was only able to evaluate the LEF for deteriorations that related to tensile strains. That said, the results from the AASHTO Road Test are limited by location, a single subgrade soil, traffic and other factors.

Because the MnROAD flexible cells were at least five years old at the time of field testing, many of the dynamic strain sensors had failed, which reduced the study to only four cells – two on the mainline and two on the low-volume test road. Only two cells out of the twelve flexible cells still had both the transverse and longitudinal dynamic strain sensors functioning.

During his analysis, Moreno found that the calculated strain for backcalculation results using a hard bottom and no hard bottom was similar, but the resulting asphalt modulus was significantly different. From this, he infers that the basin shape is what relates to the measured strain – a conclusion that could significantly shorten the calculation of strains from falling weight deflectometer deflection results over the traditional backcalculation methods.

Moreno was able to show that the MnROAD sections were linear viscoelastic. The pavement responses to the various loading tests over the course of the study were linear, but the response to speed (viscosity effect) was quite different.

It was found that transverse strains under a rolling wheel load had a longer duration than longitudinal strains. The transverse strains stayed tensile throughout the loadings whereas the longitudinal strains had a compressive component on each end of the tensile strain pulse. The measurements and the associated analysis showed that the transverse tensile strains are higher than the longitudinal strains, and the “apparent modulus” of the asphalt is lower in the transverse direction than it is in the longitudinal direction.

Consistent with the linear viscoelastic behavior, Moreno was able to show that the same layer moduli can be used to model the response of all three axle load types evaluated, single, tandem, and tridem; and strains increased as speed decreased.

Tire pressure changes from 90 psi to 130 psi did not seem to have a significant effect on the measured strains at the bottom of the asphalt. Moreno offered a possible explanation relating to the contact pressure from the tire, but it is likely that the load is more important than tire pressure at the bottom of the asphalt for the thickness of the sections evaluated, which were all over five inches thick.

Moreno calculated an apparent asphalt modulus as part of the analysis. The apparent modulus calculation started with layer moduli from backcalculation results. By adjusting the asphalt modulus to obtain the measured strain, Moreno concluded there was reasonable agreement between the backcalculated moduli and apparent moduli for the test runs at higher speeds.

The determination of load equivalency factors requires that an estimate of some terminal serviceability level be identified; that is, how many strain repetitions are required to develop cracking. Since the cells at MnROAD had not developed sufficient cracking to create MnROAD-based fatigue models, four existing models that predict the fatigue capacity of asphalt pavements were used to calculate LEF values. The four models used were the Asphalt Institute model, the Shell (Netherlands) model, the Transportation Research Laboratory (UK) model, and the CEDEX (Spain) model. The measured strains were applied to each model to calculate the LEF values as a function of the load response by axle type, load, temperature, speed, and tire pressure.

Load Equivalency Factors were calculated for each of the three axle types tested, single, tandem, and tridem axles for each of the four cells included in the testing and analysis. Figure 8 is an example of one of twelve plots of LEF presented in the report.

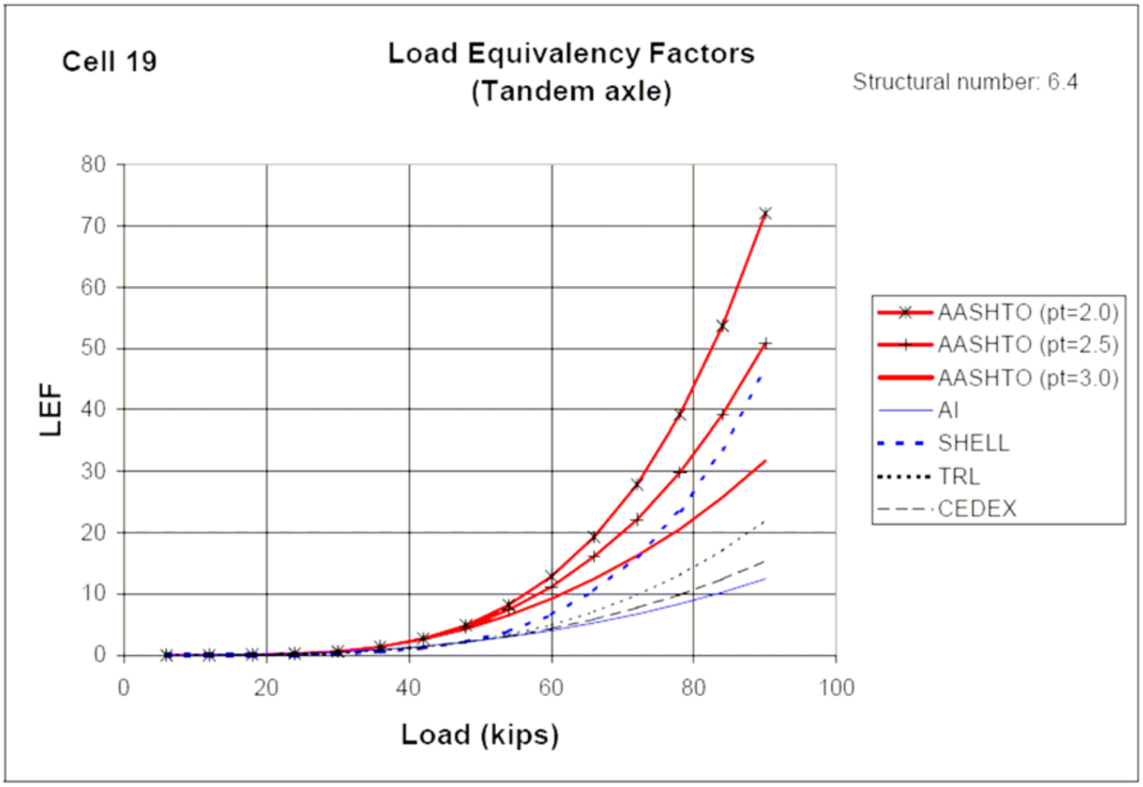


Figure IV.105.- LEF comparison ~ Cell 19 ~ Tandem axle

Figure 8. Example of Load Equivalency Factor Comparison for a Tandem Axle on Cell 19 from Moreno's report.

The LEF values Moreno derived for the cells evaluated tended to underestimate the AASHTO LEF and as the loads increased, the underestimation became more pronounced. A possible reason for Moreno's LEF values to be less than AASHTO is that the analysis is based only on the distress associated with the tensile strain at the bottom of the asphalt due to axle loads. Many other factors contribute to the overall decline in serviceability and the sum total of those other factors likely would make up a part or all of the difference. The LEF for the various fatigue models also varied significantly, as would be expected.

Rigid Pavements

The analysis of the data for load equivalency factors for rigid pavements was more problematic. As reported by Forst, the rigid data was erratic and additional work was necessary to improve the relationship between measured and predicted strains. Predicted strains were calculated from the layer properties obtained using the ILLI-BACK backcalculation program. These predicted strains were higher than the measured strains. Glasgow later, with the use of the finite element program ISAB2000, found he could relate predicted strains to measure strains by adjusting the subgrade support k-value. Since ILLI-BACK was used to backcalculate the slab stiffness and subgrade k-value in the previous work, Oman developed a process of adjusting ILLI-BACK backcalculated k-values to approximate a k-value that would produce similar deflection responses in ISLAB2000. Various slab moduli, thickness, subgrade k-values and slab lengths and widths were used to calculate responses with ISLAB2000 and the resulting deflection responses were then used in ILLI-BACK to calculate k-values. That work resulted in a graphical look-up method of determining an adjustment factor to apply to ILLI-BACK k-value results and slab modulus result that, when used in ISLAB2000, would provide predicted strains that are more consistent with the measured strains. Complications still remained in using the field data to investigate load equivalency factors because of changing temperature differentials in the slabs during testing. Also, the thinner mainline slabs were wider (14-foot) than the thicker mainline slabs (12-foot), so the comparison of critical strains at the edge of the slab could not be done on the basis of a single variable, such as axle load or axle type.

The strains in a 15-foot and 20-foot slab were compared and it was found that for otherwise similar conditions, the measured midpanel strains under the steering axle were less for the longer slab. ISLAB2000 analysis showed a similar but lower trend.

The rigid pavement testing, data processing, and analysis, however did result in a significant database of PCC strains, consisting of 4,441 records. This data will be very valuable for years to come for the purpose of comparing response predictions of various programs to field measurements.

SUMMARY OF FINDINGS AND CONCLUSIONS

The MnROAD facility, constructed on Interstate 94 about 40 miles northwest of Minneapolis, Minnesota, contained 40 test cells as part of the original construction. Construction of the test cells took place in 1992 and 1993 and the test cells were opened to traffic in August 1994. The MnROAD facility included a significant amount of instrumentation, including sensors to measure pavement strains under traffic loading and the pavement temperatures. The information from the strain and temperature sensors was used for this project.

This was an extensive study that evaluated the ability to predict pavement strains by comparing the predicted strains to measured pavement strains. The ability to do this is essential in the development of new mechanistically based pavement design procedures. Four major reports and three supporting reports were produced during the course of this study.

General Conclusions:

There were several general observations by the researchers regarding the monitoring of instrumented test sections:

- Instrumentation has a finite life and detailed tests that require the output from imbedded instruments should be done early in the life of the test section so that sufficient data can be obtained.
- The number of variables included in a pavement research facility such as MnROAD should be limited so that the influence of each independent variable on the pavement response can be investigated.

Findings:

Flexible pavement mechanistic response models ILLI-PAVE and WESLEA were compared and were found to produce similar results. The WESLEA program was selected for use in this study because it was easier to use. The strains predicted using the axle-loading parameters and backcalculated layer properties could be calibrated to reasonably approximate the strains measured in the field.

Rigid pavement mechanistic response model JSLAB-92 was found to predict much higher strains than measured in the field. The inputs for JSLAB-92 were layer thicknesses and backcalculated properties from the program ILLI-BACK. This discrepancy led to an additional task to evaluate various other pavement response models and it was found that using ISLAB2000 and dynamic subgrade k-values, the calculated strains would reasonably match the measured strains. Using the dynamic k-value concept, a series of equations were developed to estimate the dynamic k-value for the MnROAD conditions such as axle load, slab thickness, or lateral position of the wheel load.

Flexible pavement load equivalency factors could be established only for the mechanistic load response of the strain at the bottom of the asphalt. The pavement conditions had not changed sufficiently at the time of the research to include performance factors. In this analysis, it could be shown that:

- The flexible pavements were linearly viscoelastic (the load versus strain response was linear at a given loading speed, but the strain response was speed dependent indicating there was a viscous effect).

- Transverse strains under a rolling wheel load had a longer duration than the longitudinal strains; the transverse strains were higher; and the apparent modulus in the transverse direction was lower than in the longitudinal direction.

- Tire pressures in the range of 90 to 130 psi did not have a significant effect on the strains at the bottom of the asphalt.

- The strain-based load equivalency factors were all less than the AASHTO load equivalency factors.

Rigid pavement load equivalency factors were not determined during this study due to the complexities of the MnROAD rigid pavement cells and erratic strain behavior.

During the course of the study, two methods of relating ILLI-BACK results to the ISLAB2000 finite element response model were developed:

- Measured strains at the bottom of the outside edge of the slab could be reasonably predicted from ILLI-BACK backcalculated layer properties and dynamic k-value estimating equations.
- A graphical method of adjusting ILLI-BACK elastic PCC moduli and subgrade k-value was developed. The method uses the slab length and radius of relative stiffness (calculated by ILLI-BACK) as lookup variable for factors to adjust ILLI-BACK values to match ISLAB2000 predicted deflection responses.

Evaluations of the effects of slab length and slab thickness from the MnROAD data were inconclusive. The thinner slabs were also wider, countering the effect of the reduced thickness. The effect of slab length on strain as measured at MnROAD showed that strains at the bottom of the outside edge of the slab decreased slightly as the slab length increased. ISLAB2000 predicted a similar behavior but somewhat smaller effect than observed at MnROAD.

This study generated strain measurements that will be very valuable for some time to come for calibrating pavement response models to measured field conditions.

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