DIURNAL CHANGES IN PROFILE OF ELEVEN JOINTED PCC PAVEMENTS

Steven M. Karamihas
University of Michigan Transportation Research Institute
2901 Baxter Road, Ann Arbor, MI 48109-2150

Rohan W. Perera
Soil and Materials Engineers, Inc.
43980 Plymouth Oaks Blvd., Plymouth, MI 48170-2584

Thomas D. Gillespie
University of Michigan Transportation Research Institute
2901 Baxter Road, Ann Arbor, MI 48109-2150

Starr D. Kohn
Soil and Materials Engineers, Inc.
43980 Plymouth Oaks Blvd., Plymouth, MI 48170-2584

ABSTRACT

This paper examines variations in roughness that occurred over a ten-hour period in eleven jointed PCC pavements that cover a range of major design factors. The paper discusses the contribution of pavement curvature to the Mean Roughness Index (MRI). The paper presents measured changes in MRI that took place throughout the day. These measurements were conducted starting on a cool morning and ending on a clear, hot afternoon. Six of the pavements showed a significant decrease in roughness throughout the day, three of the pavements changed very little, and two increased in roughness. The majority of these pavements changed in MRI more than 0.20 m/km.

INTRODUCTION

The nominal curvature built into jointed PCC slabs depends on several factors, including base support, slab length, layer thickness and strength, reinforcement, joint type, and temperature and moisture of the concrete material during curing. (*1, 2*) Since pavement slab curvature is so heavily linked to pavement stress, these effects have been studied carefully. (*3-5*) However, very little discussion appears in the literature of the effect of pavement slab curvature on ride quality or vehicle response.

In an early study of jointed PCC pavement curvature, a committee of the Highway Research Board reported that most of the permanent slab distortion that causes "objectionable roughness" can be linked to moisture gradients in the support layer, and that temperature and moisture gradients that occur in the slabs over a daily cycle are not likely to affect ride quality. (*1*) A more recent look at profile measurements of PCC pavements showed that the "locked in" slab curvature has a strong relationship to existing roughness and to the rate at which roughness progresses. (*6*)

Although the prevailing curvature of PCC slabs is usually associated with moisture gradient, changes in slab curvature on a daily cycle are primarily caused by temperature gradient. (*7*) For example, if a cool night is followed by a hot, sunny day, the pavement will be hotter at the upper surface than at the lower surface in the afternoon. This is called a positive temperature gradient. The surface of the pavement slabs, heated by the sun and air, expand relative to the bottom and the edges curl downward. In the night and early morning hours when the temperature at the pavement surface is lower than the temperature under each slab, the surface contracts and the edges tend to curl upward. These changes are superimposed on the nominal shape of each slab. Usually, a pavement is always curled in one direction or another, and the temperature gradient influences the severity of the curvature. (*7, 8*)

This paper reports measured changes in Mean Roughness Index (MRI) that took place on eleven PCC pavement sections over a ten-hour period. (MRI is the average of the International Roughness Index (IRI) from the left and right side of the lane.) The measurements were made starting on a cool morning followed by a clear, hot day. The experimental measurements are described. The changes in slab curvature and the resulting changes in MRI of one section are discussed in detail as an illustrative example. The example demonstrates the strong contribution of slab curvature to overall road roughness and the magnitude of roughness variation that is possible on a daily cycle. A summary of the changes in MRI is then provided for all eleven pavement sections. The paper shows that an individual profile measurement of a jointed PCC road is merely a single sample of the roughness. In addition, the magnitude of changes in jointed PCC roughness that occur on a daily cycle can be large enough to affect the way a road is judged by a pavement management engineer.

EXPERIMENTAL MEASUREMENTS

The variation in roughness of eleven pavement sections was measured over a ten-hour period on March 28, 1997. These sections were on US-23 Northbound, just north of the border between Michigan and Ohio. They were part of the Long-Term Pavement Performance (LTPP) Special Pavement Studies experiment "Strategic Study of Structural Factors for Rigid Pavements" (SPS-2). (*9*) All of these pavement sections are doweled jointed PCC with joints spaced 4.6 meters apart. The annual traffic loading of this site is estimated to be 890,000 ESALs. Some relevant design features are listed in table 1. The structural design factors included in the SPS-2 experiment cover a factorial matrix of two

PCC layer thickness values, two values of flexural strength, and three support layer variations. This should cover twelve overall designs. For logistical reasons, the measurements made for this experiment covered only ten of these twelve possible combinations. An eleventh section (260253) was also measured that is a special design in common use in Michigan.

The sections are listed in the order they appear to passing vehicles. These sections were all built in the outside lane, and were spread out over a 2.5-km long stretch of road. They were placed in near proximity so that they would all experience approximately the same traffic and environment. (An exit appears between section 260220 and section 260215, but it is sparsely used.)

Table 1. Design features of test sections.

LTPP Section Number	Lane Width (m)	PCC Flexural Strength (MPa)	Layer Thickness (cm)			Layer Type	
			Layer 1	Layer 2	Layer 3	Layer 2	Layer 3
260217	4.27	3.8	20.3	15.2	—	LCB	—
260213	4.27	3.8	20.3	15.2	—	DGAB	—
260221	4.27	3.8	20.3	10.2	10.2	PATB	DGAB
260224	4.27	6.2	27.9	10.2	10.2	PATB	DGAB
260216	4.27	6.2	27.9	15.2	—	DGAB	—
260220	4.27	6.2	27.9	15.2	—	LCB	—
260215	3.66	3.8	27.9	15.2	—	DGAB	—
260223	3.66	3.8	27.9	10.2	10.2	PATB	DGAB
260222	3.66	6.2	20.3	10.2	10.2	PATB	DGAB
260253	3.66	3.8	26.7	10.2	7.6	OGDC	AGG
260214	3.66	6.2	20.3	15.2	—	DGAB	—

LCB - Lean concrete base DGAB - Dense graded aggregate base PATB - Permeable asphalt treated base
AGG - Aggregate base OGDC - Open graded drainage course

Each of the eleven pavement sections was measured a minimum of 31 times starting at 5:07 AM and ending at 3:42 PM. The delay between measurements was dictated by the time it took to drive over the sections then return to the starting point. The measurements were performed on a cool morning followed by a warm, clear day. Hourly temperature measurements before and during the experiment are displayed in figure 1. The figure shows the overall range and the average for each hour. The temperature data was extracted from the LTPP database.

The experiment follows a cool night, and covers a period of gradual change in air temperature from 11˚C in the morning to 23˚C in the mid-afternoon. The ground

underneath the pavement was likely to be particularly cool compared to the pavement surface, since the measurements took place in early spring. Since the sky was clear, the change in surface temperature is likely to have been even greater than the change in air temperature. These conditions gave rise to a significant positive temperature gradient.

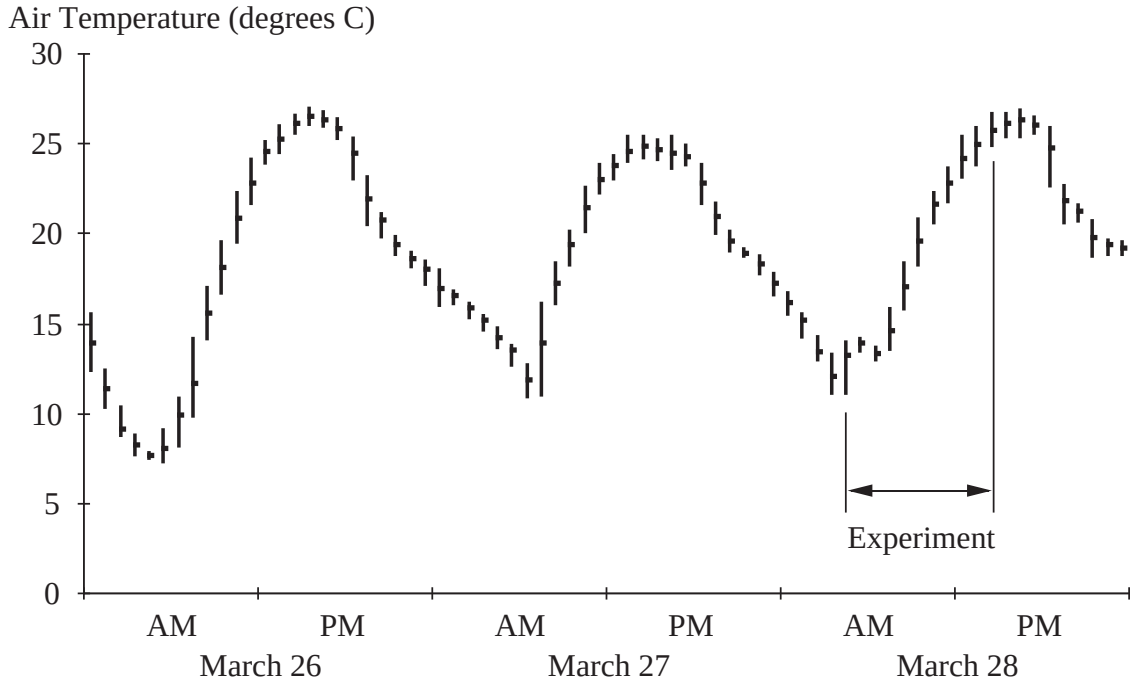

Figure 1. Air temperature during the experiment.

SECTION 260213

Figure 2 shows the change in mean roughness index (MRI) of section 260213 with time during the experiment. In the morning, the MRI is approximately 1.5 m/km. The MRI decreases rapidly until noon, and settles to a value of about 1.1 m/km. This change is significant, because each level falls within a different roughness classification assigned by many state departments of transportation. In several states, 1.1 m/km is considered “good”, and 1.5 m/km is considered “fair”. In others, 1.1 m/km is considered “very good” and 1.5 m/km is considered “good”. (*10, 11*)

Note that the change in MRI of section 260213 throughout the day followed a strong trend, but some scatter is also present. This was most likely caused by variation in lateral positioning between measurements. Although the driver of the profiler made a conscious effort to maintain a consistent lateral tracking position during all of the measurements, no special equipment was used to assist him. Thus, variations in lateral position of up to 30 cm are expected to have occurred. (*12*) The level of scatter present in the MRI time series plots of all of the pavements in this experiment can be attributed to variations in the lateral tracking position of the profiler. (*13*)

Independent measurements of MRI made in 1997 for the LTPP study are consistent with the values measured for this experiment. For example, the average MRI values for LTPP profile data collected on April 15, 1997 on section 260213 is 1.12 m/km. That set of measurements was made at about 1 PM on a day in which the temperature changed about as much as it did on March 28, 1997. For example, the air temperature was about 5˚C at 9 AM and increased steadily to about 20˚C at 2 PM. Measurements in the LTPP database collected on July 1, 1997 have an average MRI of 1.48 m/km. Those measurements were made at about 11 AM on a day in which the air temperature only ranged from 22˚C to 29˚C.

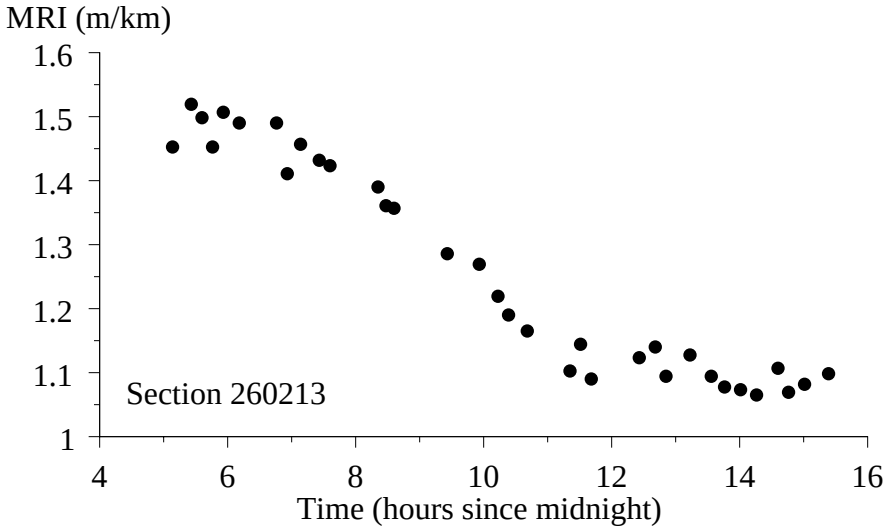

Figure 2. MRI versus time of section 260213.

Curvature of the slabs in section 260213 contributed significantly to the overall roughness. Figures 3 and 4 show the power spectral density (PSD) of left profile slope from the first and last measurement taken on section 260213, respectively. Note that PSD of slope is provided, rather than elevation. This is because the amplitude of road profile elevation varies by several orders of magnitude over the range of wavelengths shown, whereas amplitude of profile slope is relatively consistent. (*14*) Thus, the details that distinguish one road from another are more obvious in a plot of slope PSD. When plotted on a linear scale, the area under the PSD in any range between 0.033 and 0.8 cycles/m is a crude indicator of the relative contribution of each waveband to the IRI and, thus, the MRI. (The gain of the IRI filter to a slope input ranges from 0.5 to about 1.65 over that wave number range. (*15*))

The PSD of the profile from 5:07 AM includes a rather narrow peak at a wave number of about 0.22 cycles/m. This means that the road includes some periodic roughness with a characteristic wavelength of 4.6 meters. (The wavelength is the inverse of the wave number.) This is the joint spacing, and the peak is caused by a recurring slab shape. The peak at about 0.44 cycles/m is most likely a second harmonic of the slab shape. The PSD shows some significant content in the long wavelength (short wave number) range, but the majority of the roughness is accounted for by the two peaks. Figure 4 shows a much lower

peak at a wave number of 0.22 cycles/m. This indicates that whatever slab shape elevated the roughness so much at 5:07 AM was much less significant in magnitude at 3:42 PM. This is consistent with the nearly 30 percent decrease in MRI throughout the day.

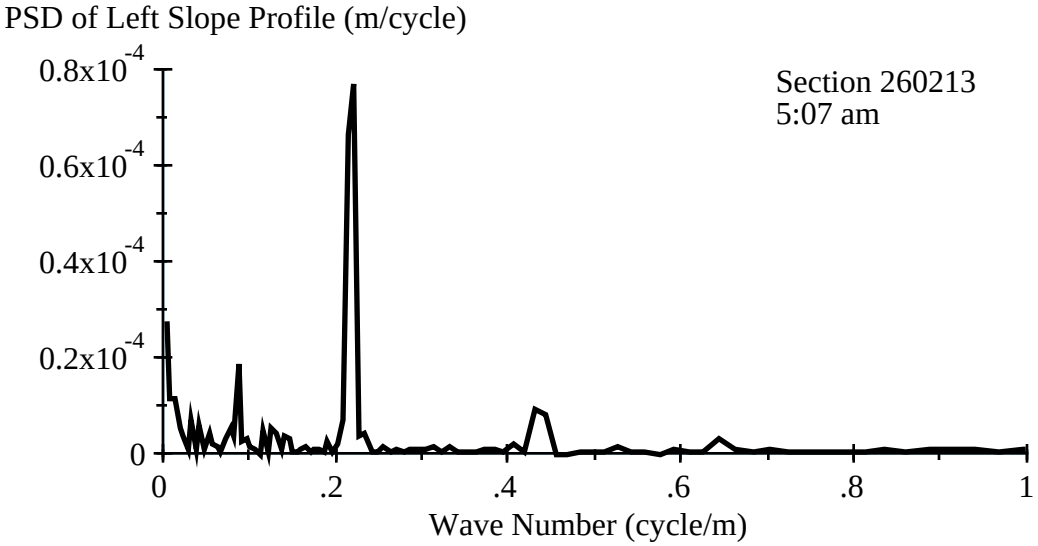

Figure 3. PSD of left profile slope, section 260213 at 5:07 AM.

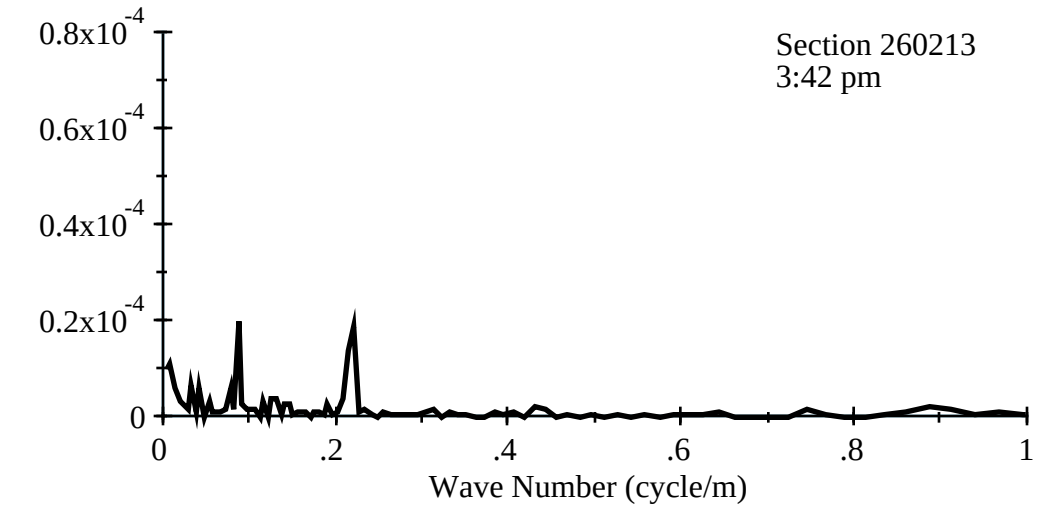

Figure 4. PSD of left profile slope, section 260213 at 3:42 PM.

The slabs in section 260213 were curled upward (i.e., the edges were higher than the center). The onset of positive temperature gradient throughout the day caused the slab edges to move downward, which decreased the overall slab curvature. This is why the roughness decreased throughout the day. Figure 5 shows a portion of the left elevation profile from the morning with the very long and very short wavelengths filtered out to help show the slab shape. The high points in the plot occur at slab edges. In the morning, the profile at the slab edges are 1-3 mm above the profile at the slab centers.

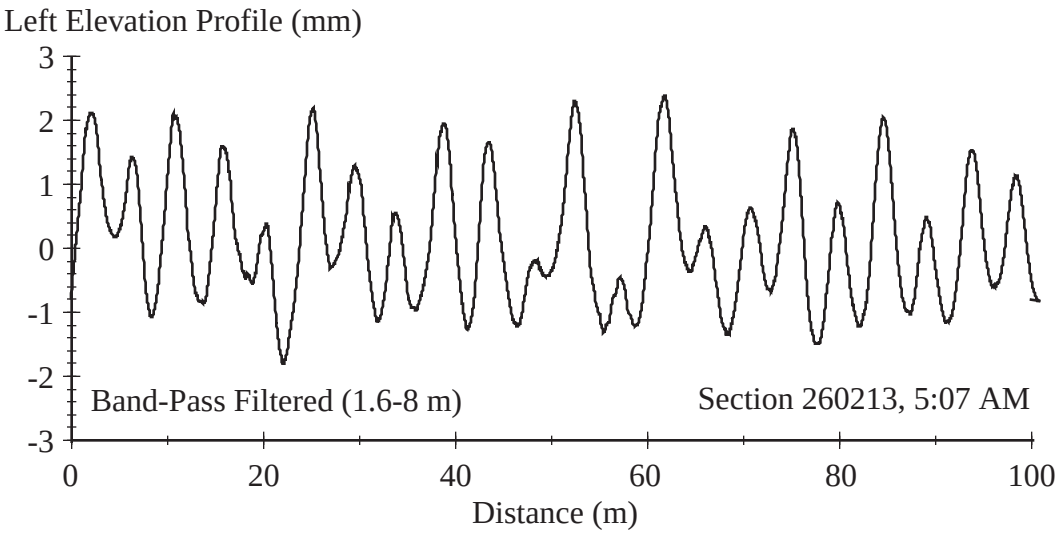

Figure 5. Slab shape on section 260213, 5:07 AM.

Figure 6 compares the profile collected in the morning to one collected in the afternoon over the first 20 meters of the section. (Note that the profiles are offset vertically so they can be distinguished from each other.) In the figure, the peaks in both measurements occur at the slab edges and the valleys occur at the slab centers. The difference in elevation between the slab edges and the slab centers is significantly smaller in the profile collected in the afternoon. On section 260213, the uplift of the edges decreases by more than 1 mm in the afternoon on many of the slabs. This is consistent with observations in the literature of change in corner uplift of up to 2 mm on similar pavements. (*7*, *8*)

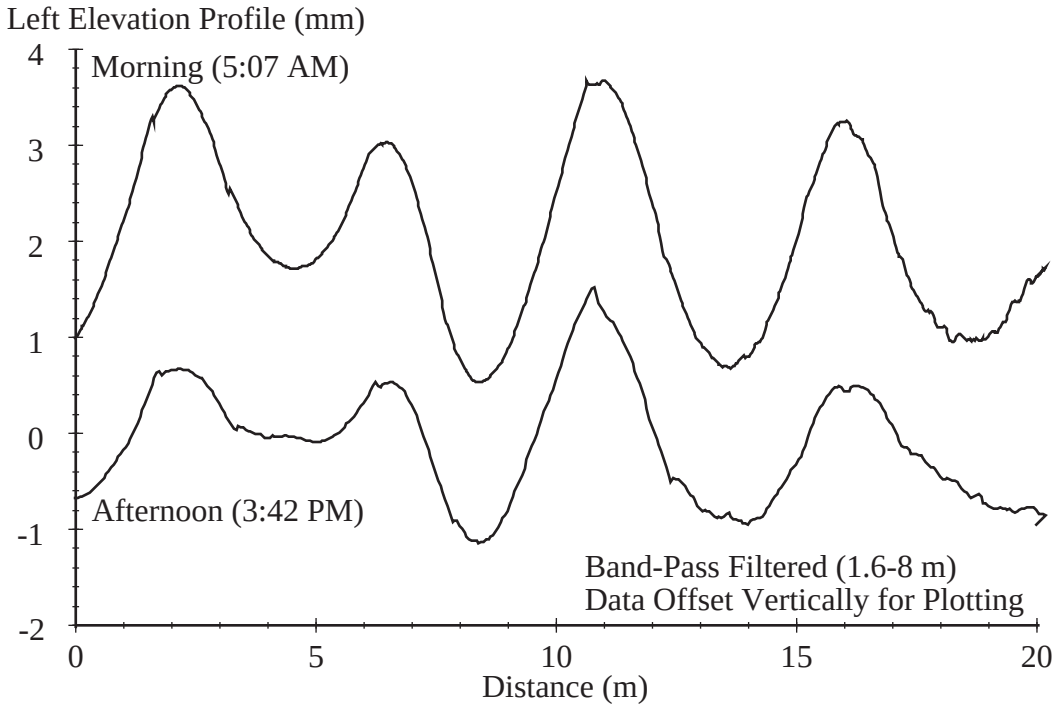

Figure 6. Slab shape on section 260213, 3:42 PM.

SUMMARY OF MRI VARIATIONS

Table 2 lists the change in MRI of all of the sections in the experiment. A negative value of change indicates that the MRI decreased throughout the day. The table also lists the MRI in the early morning. (The early morning values are listed because these were measured when the temperature gradient was probably lowest.) Of the eleven pavements measured in this experiment, six showed a significant decrease in MRI throughout the day. These all exhibited the same qualitative behavior as section 260213, but their roughness did not all change as dramatically. Close inspection of the profiles revealed that the direction of slab curling did not reverse in any of the pavements. The temperature changes only affected the severity of curling.

Table 2. Summary of changes in MRI.

LTPP Section Number	MRI, Earliest Measurement (m/km)	MRI Change (m/km)
260217	0.92	NC
260213	1.45	–0.40
260221	0.99	+0.10
260224	1.01	NC
260216	1.39	–0.30
260220	1.34	–0.40
260215	1.26	–0.15
260223	0.91	NC
260222	1.16	–0.20
260253	1.14	+0.20
260214	2.08	–0.40

NC - No change

The MRI of three of the pavements changed very little throughout the day. Figure 7 shows the MRI versus time of one such pavement. This pavement, section 260217, is next to section 260213. It is also of the same design, except it had a lean concrete base rather than a dense graded aggregate base. Inspection of the profile plots reveals that it has very little slab curvature and the slab shape does not change throughout the day, nor is there any systematic change in the profile.

Only two of the eleven pavements in the experiment increased in roughness throughout the day: section 260253 and 260221. Both of them had slabs with a curled downward shape (i.e., convex up). Figure 8 shows the MRI of section 260253. This design was considered a “control” section in the SPS-2 experiment. It is a typical PCC design for Michigan highways. It differs from all of the other pavements in the experiment because it is on an open graded drainage course. This probably allowed the underside of the slab to desiccate quickly during curing, and may account for the curled downward shape of the slabs. Since

the slabs were curled downward, the onset of a positive temperature gradient with time caused the curling to get more severe throughout the day, and the roughness to increase.

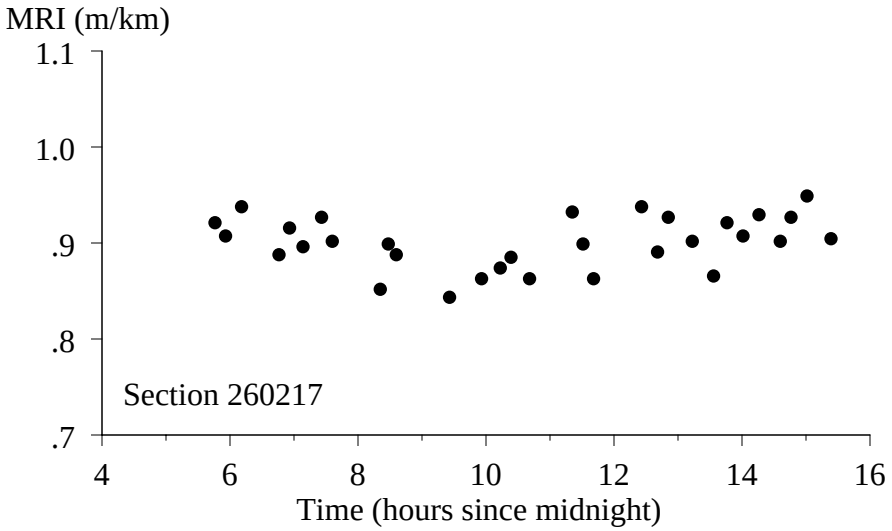

Figure 7. MRI versus time of section 260217.

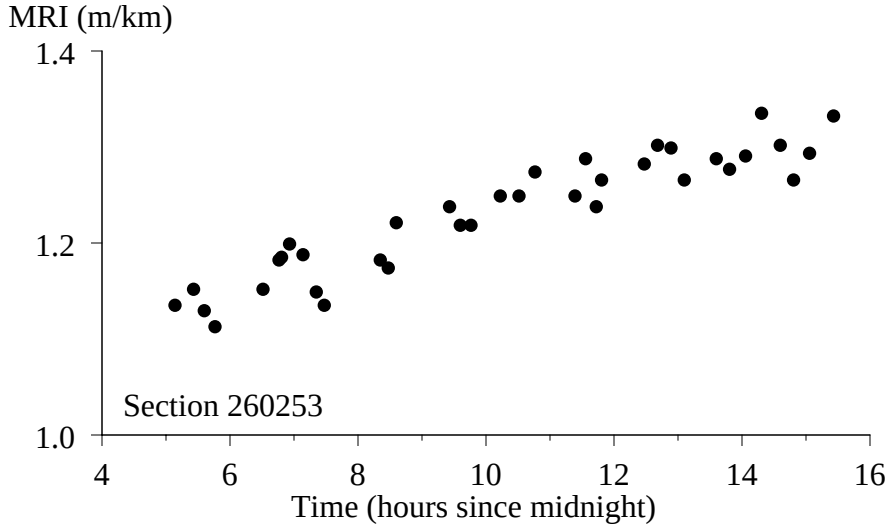

Figure 8. MRI versus time of section 260253.

Overall, sections with high roughness in the early-morning hours decreased in roughness the most by afternoon. (See table 2.) This suggests that sections with the highest level of built-in curling exhibited a larger range of slab movement. To help search for trends that relate changes in roughness to design factors, table 3 lists the changes in MRI with the pavements arranged by structural design. Each row in the table covers a unique combination of flexural strength and thickness of the first layer. Each column covers a unique set of base layer properties. Note that all of the pavements with a dense graded aggregate base decreased in roughness throughout the day. This may be because it is not a bonded base like the others, so it does not help resist changes in curling. Indeed, the highest level of curling was observed in the pavements with a dense graded aggregate base.

On the other hand, a very large change in roughness was also observed in one of the pavements with a lean concrete base, which is bonded. Also note that the increases in roughness observed in this experiment were of a lesser magnitude than the decreases in roughness. This is because a much lower thermal stress is needed to lift pavement edges than to push them into the ground.

Table 3. Summary of changes in MRI by base type.

Layer 1 Thickness (cm)	PCC Flexural Strength (MPa)	MRI (m/km) with a base type of:		
		DGAB	PATB	LCB
20.3	3.66	–0.40	+0.10	NC
20.3	4.27	–0.40	–0.20	—
27.9	3.66	–0.15	+0.05	—
27.9	4.27	–0.30	NC	–0.40

DGAB - Dense graded aggregate base LCB - Lean concrete base
PATB - Permeable asphalt treated base NC - No change

CONCLUSIONS

Overall, this experiment demonstrated that significant changes in roughness of PCC pavement on a daily cycle are possible. Changes in roughness of 0.40 m/km were observed. That is approximately double those found in a previous analysis of LTPP profile measurements of jointed concrete. (*13*) However, the measurements performed for this paper were performed on a day that was likely to cause somewhat extreme changes in roughness.

Eight of the eleven pavements exhibited slab curvature that contributed to roughness during the entire experiment. The observed changes in roughness were caused by changes in temperature gradient, and the resulting effect on slab curvature. The level of change that can be expected depends strongly on structural factors and the curvature of the slabs that was built-in during the curing process. In this set of observations, changes in air temperature affected the severity of curling, but never reversed the direction.

This paper demonstrates that an individual profile measurement of a jointed PCC road is merely a single sample of the roughness. Pavement management engineers must be aware of the cyclic changes in roughness that are possible on their road system and plan accordingly. In network-level roughness monitoring activities, it is not practical to administer special procedures to control the timing of profile measurements. Nor is it practical to monitor pavement sections at more than one time of day. However, the date, temperature, and weather conditions should be recorded with each roughness measurement to aid the engineer in interpreting results. If annual data are used in a pavement management

system to project maintenance needs, the prediction may be improved by attempting to be consistent in the timing of the measurements. Certainly, any detailed study of the roughness of a jointed PCC pavement section must be done with strict control over the timing of the measurements, and the weather conditions should be recorded.

The observations presented in this paper are by no means a complete coverage of potential diurnal variations in road profile. A more complete version of this experiment is recommended in which the same set of pavements are measured throughout the day at least once per season for at least a year. In particular, measurements of a hot, clear fall day are expected to yield a unique set of results. A repeated experiment on a cloudy day with relatively constant temperature would provide a "control" condition. Coverage of several consecutive seasons would help distinguish seasonal and diurnal changes in roughness from each other, and from steady changes in roughness with time caused by conventional pavement wear. The value of the experiment would also be greatly enhanced if direct measurements of the temperature distribution throughout the depth of the pavement were available.

ACKNOWLEDGMENTS

The authors would like to thank the Turner-Fairbanks Highway Research Center (TFHRC), which provided use of the ProRut for the experiments reported in this paper.

REFERENCES

1. *Highway Research Board Proceedings*, Vol. 25 (1945) pp. 200-250.
2. Ytterberg, R. F., "Shrinkage and Curling of Slabs on Grade." *Concrete International Design and Construction* (April 1987).
3. Darter, M. I., et al, "Support Under Portland Cement Concrete Pavements." *National Cooperative Highway Research Program Report 372* (1995) 50 p.
4. Thomlinson, J., "Temperature Variations and Consequent Stresses Produced by Daily and Seasonal Temperature Cycles in Concrete Slabs." *Concrete and Construction Engineering* (1940).
5. Westergaard, H. M., "Streeses in Concrete Pavements Computed by Theoretical Analysis." *Public Roads*, Vol. 7, No. 2 (1926).
6. Byrum, C. R., "Development of a High-Speed Profile Based Slab Curvature Index for Jointed Concrete Pavements." Ph.D. Dissertation, University of Michigan (2000).
7. Lowrie, C. and Nowlen, W. J., "Colorado Concrete Pavement and Subbase Experimental Project." *Highway Research board Bulletin 274* (1960) pp. 150-161.
8. Poblete, M. et al, "Field Evaluation of Thermal Deformation in Undoweled PCC Pavement Slabs." Transportation Research Record 1207 (1989) pp. 217-228.

9. Perera, R. W., et al, “Investigation of Development of Pavement Roughness.” *Federal Highway Administration Report FHWA-RD-97-147* (1997) 244 p.

10. “A Summary of Pavement Performance Data Collection and Processing Methods Used by State DOTs.” *Federal Highway Administration Report FHWA-RD-95-060*, (1994) 62 p.

11. Gramling, W.L., “Current Practices in Determining Pavement Condition.” *National Cooperative Highway Research Program Synthesis of Highway Practice 203*, (1994) 57 p.

12. Sayers, M. W. and Gillespie, T. D., “The Ann Arbor Road Profilometer Meeting.” *Federal Highway Administration Report FHWA/RD-86/100* (1986) 237 p.

13. Karamihas, S. M. et al, “Guidelines for Longitudinal Pavement Profile Measurement.” National Cooperative Highway Research Program Report 434 (2000) 75 p.

14. Sayers, M.W., “Characteristic Power Spectral Density Functions for Vertical and Roll Components of road Roughness.” American Society of Mechanical Engineers. *AMD-Vol. 80*. (1986) pp. 113-129.

15. Sayers, M. W., “On the Calculation of International Roughness Index from Longitudinal Road Profile.” *Transportation Research Record No. 1501* (1995) pp 1-12.