TechBrief
JULY 2010 | FHWA-HIF-10-010

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U.S. Department of Transportation
Federal Highway Administration

Impact of Temperature Curling and Moisture Warping on Jointed Concrete Pavement Performance

This TechBrief summarizes the results of a study on curling and warping in jointed concrete pavement (JCP). Profile measurements, following quality assurance plans developed under the study, were collected in all U.S. climate zones, diurnal periods, and seasons of the year to obtain sufficient data to fully characterize slab curvatures. Both functional and structural pavement performance were measured to correlate performance to curling and warping. Products of the study include a new technique that quantifies the magnitude of JCP curling and warping and a system to assess the influence of diurnal and seasonal changes on JCP curvature and pavement unevenness.

Introduction

Curling and warping are often influential factors affecting the structural (e.g., cracking) and functional (e.g., smoothness) performance of jointed concrete pavements (JCPs). Examining the causes and effects of curling and warping provides a better understanding of how to minimize or prevent these phenomena. In turn, pavements can be built to last longer, require less maintenance, and provide excellent ride quality.

This technical brief reports findings from a Federal Highway Administration (FHWA) research project: Inertial Profile Data for Pavement Performance Analysis (FHWA Contract No. DTFH61-02-C-00077). These findings were reported in a paper presented at the 6th Symposium on Pavement Surface Characteristics (Chang 2008). The goals of the research project were to better understand the curling and warping phenomena and to find efficient ways of minimizing their impact.

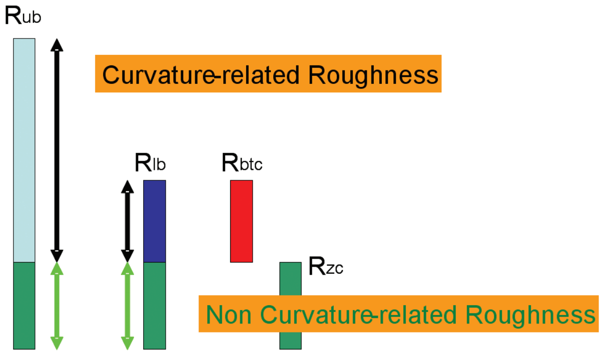

FIGURE 1. Decomposition of roughness related to curvature (Rub = upper bound roughness; Rlb = lower bound roughness ; Rbtc = built-in curvature roughness; Rzc = zero-curvature roughness).

Major Findings

Among major findings from this study, JCP roughness can now be decomposed to a curvature-related component and a non-curvature-related component (see figure 1). Summarized major findings are described in this TechBrief in the following categories:

- Measurement of curling and warping.
- Profile synchronization and joint identification.
- Second-Generation Curvature Index (2GCI).
- Impact of slab curl/warp on pavement roughness.
- Joint functionality analysis.

Measurement of Curling and Warping

Data collection was a major component of this research effort. The field data collection constituted a significant portion of the project resources and therefore was done with the greatest care to ensure that information collected would be useful in subsequent analysis. Quality assurance is the key for such a large data collection effort. Before data collection began, quality assurance plans were developed for all data collection tasks.

Data collection began in late March 2003 and ended in mid-June 2004. During this 15-month period, a total of 38 JCP pavement test sites throughout the country were instrumented and profiled.

Some of the testing protocols developed for the Long-Term Pavement Performance Program Research Grade field data collection were adapted for use on this project: protocols for profiling, falling-weight deflectometer testing, temperature measurements, and site identification.

Profile Synchronization and Joint Identification

A robust and effective procedure was developed to synchronize profiles prior to objective curl/warp analysis. The goal of this pre-process was to identify joint locations based on respective profiles. Individual slab profiles could then be isolated to correctly analyze the curled/warped slab shapes.

Profile synchronization was successfully accomplished by successive applications of cross correlation and adjustments in sampling intervals on filtered, decimated, and non-decimated profiles. This process proved to be very efficient and effective.

Joint identification was also successfully performed by searching for locations at which narrow dips appeared in multiple synchronized repeat measurements. The dips were identified by applying a high-pass filter, normalizing by the root mean square (RMS), and searching for locations in the profile where the elevation

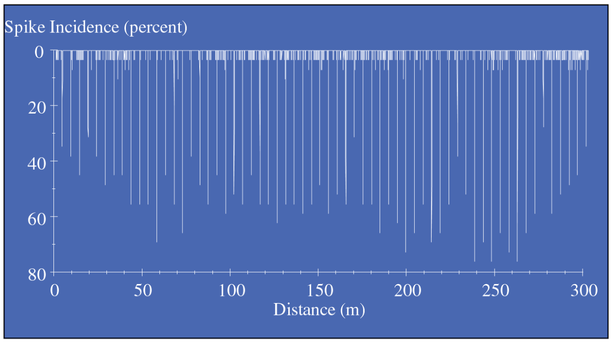

FIGURE 2. Joint identification results. Example of a “spike profile” from a test section in the study. The spikes indicate joint locations identified within a profile through analysis.

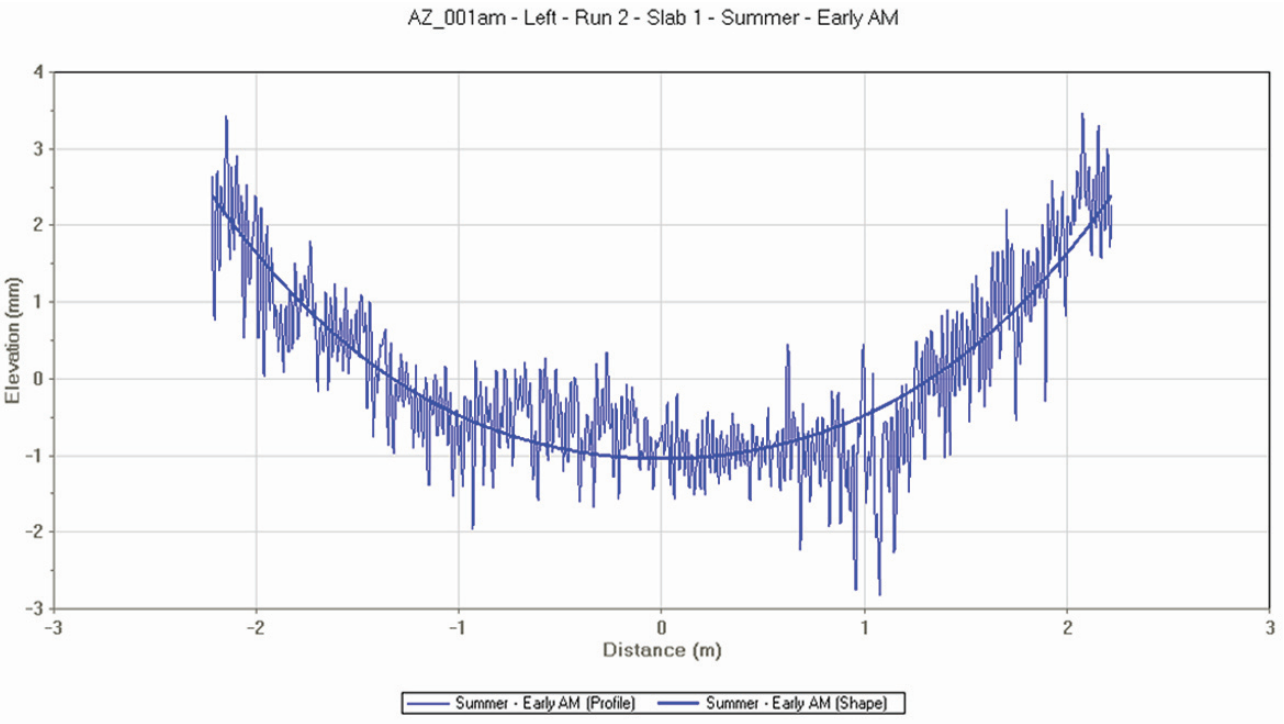

FIGURE 3. Example of a Second-Generation Curvature Index (2GCI) fitting. The "chattered" line is the detrended raw profile, and the thicker, smoother line is the fitted line.

value was below the zero line by a threshold value (see figure 2).

The above procedures can readily be applied to any profile measurements for similar analyses provided the profiles are collected according to the quality assurance plan developed under this study.

Second-Generation Curvature Index

Through a detailed technical review on existing curvatures indexes, it was found that the Byrum Curvature Index (BCI) algorithm developed by Byrum (2001) and the RMS index for curvature contain shortcomings that compromise their usefulness. As a result, a Second-Generation Curvature Index (2GCI) was developed to overcome some of the inherent shortcomings of the BCI and other methods for quantifying slab curvature (see figure 3).

Based on Westergaard's (1926, 1927) curling equations and real-world joint restraints, the 2GCI seeks to better quantify slab curvature on a level that is more representative of the slab shape as a whole. In doing so, the 2GCI adopts an approach to derive a curvature metric that fits hypothesized slab geometries to their measured slab profile. While almost any geometric model can be used, a Westergaard-based model is considered most appropriate. The resulting model parameters of the 2GCI have connection to the physical parameters that describe a JCP system subjected to curling and warping. Since these model parameters characterize effects beyond what Westergaard considers directly (such as slab restraint due to joint reinforcement), they would instead be termed "pseudo" parameters, i.e., pseudo strain gradient and pseudo radius of soil reaction.

Slab Curvature Analysis

The 2GCI algorithm was proven as an appropriate concept and tool to characterize a slab curvature index that is stable, portable, and mechanistic in nature, provided the profile data are isolated for each slab via profile synchronization and joint finding. A tool based on the 2GCI algorithm was developed and utilized to analyze slab shapes of profiles under this study.

Diurnal changes (changes during a day) in slab curvatures were captured with the profile data and the curvature index values. The resulting curvature values and their diurnal variation for a given slab clearly described how a slab curls under *in-situ* conditions. The curling pattern was found to be curled up at different levels, curled down at different levels, or even changed in both directions.

Considering an entire site for curvature analysis, the slabs may be curled differently in terms of level of curvature or even direction at a moment in time. The spatial variability can be observed from a global curvature plot where all slab curvature values from selected runs from each period are plotted. The variability of 2GCIs for all slabs can also be statistically expressed in box plots where the median, maximum, minimum, first quartile, and third quartiles are plotted for visualization, as shown in figure 4.

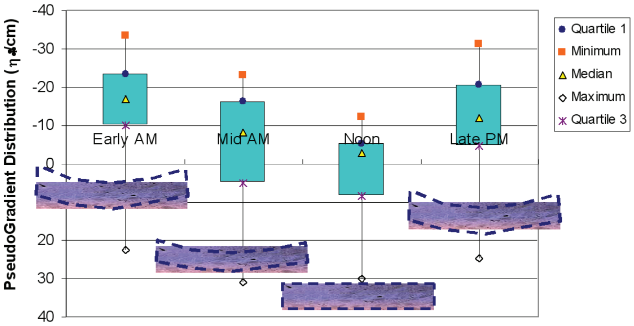

FIGURE 4. Diurnal curvature analysis. Example of a box plot for a test section where most of the slabs are curled up.

The seasonal variation of slab curvatures (found to be 8 microstrain/cm or less for the mean values) was generally equal to or smaller than the diurnal variation. The trend of seasonal slab curvatures may be different for the different diurnal analysis periods (such as early morning vs. noon).

Curvatures for the travel lane and adjacent lane are not necessarily correlated. In other words, corresponding slabs from both lanes may not be curled at similar levels or even in the same direction. This is most likely an indication that adjacent lanes were constructed at different times.

For all of the test sites around the country, the majority had negative mean curvature values (i.e., curled up). However, there were also sites where the majority of slabs were curled down or even alternating in the direction of curl. The extreme mean curvatures (averaged for all slabs of all runs for all sites) were observed at -12.6 microstrain/cm (curled up) and +15.7 microstrain/cm (curled down).

These findings prove the 2GCI to be an effective tool for studying slab curl and warp. Studies on variability of slab curvature for a given site would not be possible without this method.

Impact of Slab Curl/Warp on Pavement Roughness

A comprehensive system and tools were developed to assess curling and warping effects on ride quality. The system, the RoCK chart (see figure 5), identified five distinct categories of relationships to cover all possible site conditions and behaviors to quantify the impact of curling and warping effects on pavement roughness.

Based on analysis using this system for the sites tested under this study, it can be shown that diurnal (or changes during a day) impacts of slab curling on the Half-car Roughness Index can be as high as 0.63 m/km with an average around 0.16 m/km. This finding suggests that it may be prudent for more emphasis to be placed on the timing of roughness measurements within specifications, particularly for agencies working under incentive–disincentive

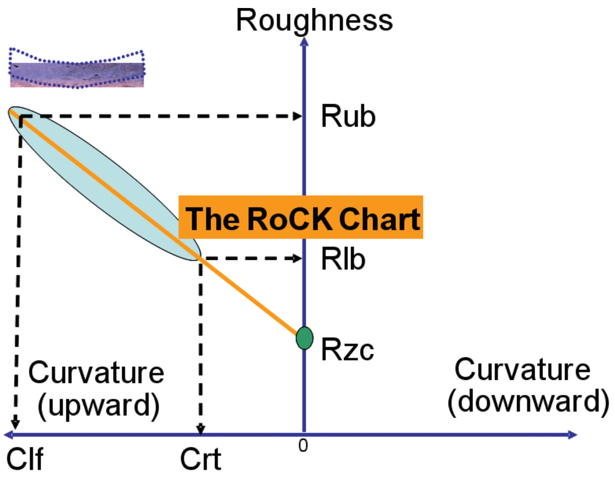

FIGURE 5. Curvature-roughness analysis. A roughness-curvature (RoCK) diagram for Curvature-Roughness Analysis showing the following parameters: Rub = upper bound roughness; Rlb = lower bound roughness; Crt = right-bound curvature; Clf = left-bound curvature; Src = roughness curvature slope; Rzc = zero-curvature roughness.

specifications. This observation could also apply to maintenance programming as it is likely that the estimated functional condition (roughness) of the pavement network at the time of the survey may vary significantly, depending on the timing of testing and curling characteristics of the pavement. Based on the observations from this study, this issue must be dealt with on a site-by-site basis since it has been demonstrated that diurnal and seasonal effects vary significantly between sites.

The comprehensive system and analysis tools developed for analyzing ride quality in relation to curling and warping effects can be used by State agencies and contractors to improve smoothness specifications, pavement management systems, and construction practices in hopes of minimizing pavement roughness.

Joint Functionality Analysis

An analysis framework and system were developed to examine profile data to characterize joint functionality and estimate joint faulting. This system was used to first isolate profile data at joints and then to process the data to obtain fitted slab edge shapes and joint faulting. The slab edge shapes from the diurnal runs, along with the pavement temperature gradients, were used to determine the joint functionality parameter based on a least-square linear fit technique. Significant variability of joint edge geometry was often observed even in the same pavement section under the same design and construction.

A robust joint functionality tool was developed and used for identifying whether a joint was "working" or "locked." Additional viewer tools were developed for spatial and statistical understanding of changes in joint functionality on a diurnal or seasonal basis (see figure 6).

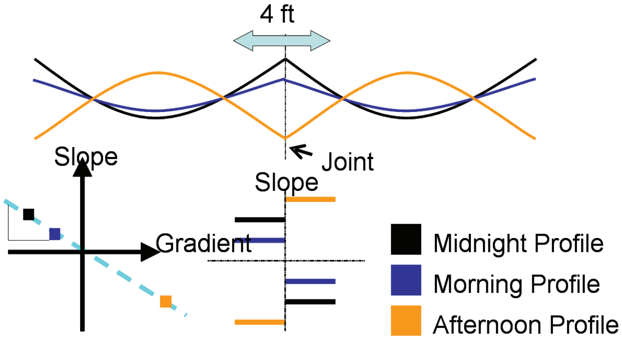

FIGURE 6. Joint functionality analysis showing diurnal effects.

Variability of joint functionality throughout any given test site was found to be common. Joint functionality for the main lane and adjacent lanes did not always follow a similar trend. Joint faulting was limited for most of the test sites, likely due to the presence of dowels and relatively young age of the test sections. A viewer tool was developed to facilitate the analysis of joint faulting on both a diurnal and seasonal basis. No clear relationship between load transfer efficiency and joint functionality could be established. This is likely due to the limited amount of falling-weight deflectometer data collected under this effort.

Who Benefits From This Study?

- **Pavement Designers,** who can use the products to improve pavement designs and minimize both initial and life-cycle costs.
- **Contractors,** who can optimize their construction practice to minimize built-in curling and to better achieve smoothness specifications.
- **Materials Suppliers,** who can integrate the results from this study into their materials selection and proportioning procedures.
- **Specification Developers,** who can determine what variables should be controlled to optimize construction quality and long-term performance, thus minimizing life-cycle costs.

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Research—This TechBrief was developed by George Chang, Ph.D., P.E., Robert Rasmussen, Ph.D., P.E., David Merritt, P.E., and Sabrina Garber from the Transtec Group, as well as Steve Karamihas from the University of Michigan Transportation Research Institute as part of FHWA’s Concrete Pavement Technology Program research activity. This study was conducted under FHWA Contract No. DTFH61-02-C-00077, Inertial Profile Data for Pavement Performance Analysis.

Distribution—This TechBrief is being distributed according to a standard distribution. Direct distribution is being made to FHWA’s field offices.

Key Words—Jointed concrete pavements, curling, warping, pavement profiles, pavement distress, pavement performance, built-in curling, slab curvature, profile analysis

July 2010

FHWA-HIF-10-010