QUANTIFYING THE IMPACT OF JOINTED CONCRETE PAVEMENT CURLING AND WARPING ON PAVEMENT UNEVENNESS

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ABSTRACT

Curling and warping of jointed concrete pavement (JCP) are well-known phenomena. It is a common belief that this behavior may impact pavement unevenness, and thus driver comfort. This relationship has been difficult to quantify in the past due to lack of adequate field measurements and appropriate analysis techniques. To address this issue, the United States Department of Transportation Federal Highway Administration (FHWA) initiated the research project, “Inertial Profile Data for Pavement Performance Analysis.” This is arguably the most extensive study on JCP curling and warping conducted by this agency to date. The resulting products from this study included a new technique termed the Second Generation Curvature Index (2GCI) that quantifies the magnitude of JCP curling and warping. A system termed Rasmussen-Chang-Karamihas (RoCK) diagram was also developed to assess the influence of diurnal and seasonal changes on JCP curvature and pavement unevenness. The resulting system is anticipated to change how measurement of JCP unevenness should be made, and how JCP unevenness criteria should be specified. Thus, the products from this study will serve both owner-agencies and practitioners alike as powerful tools for to better manage their concrete pavements.

1. INTRODUCTION

Curling and warping of jointed concrete pavement is a well-know phenomenon. In the past, proper measurement and characterization of curling/warping, particularly for the purpose of relating it to pavement performance, has not been done in a way that takes full advantage of modern measurement technology and analytical tools. Proper pavement profile measurement for studying curling and warping needs to capture JCP joints and approximate slab shapes. In order to accomplish this, profile measurement quality assurance plans were established and executed under the FHWA study, described previously. Furthermore, experimental plan were developed to cover all U.S. climate zones, all diurnal periods, and all seasons of the year in order to obtain sufficient information to fully characterize slab curvatures. Finally, both functional and structural pavement performance was measured in great detail in order to correlate performance to curling and warping.

There were several questions that needed to be answered prior to the analysis design. These correspond to the goals of this study. The first question is whether slab curvature can be related to pavement performance, and what analytical methods can accomplish that best. The second question is whether a limit on allowable slab curvature under specific environmental and support conditions ensures improved pavement performance (structural and functional). The final question is what construction methods or design characteristics can help achieve improved performance in light of the answers to the first two questions.

In order to answer these questions, data analysis and model development need to be structured such that slab curvature values can be adequately obtained and subsequently interpreted in a systematic manner, considering the very large volume of data. This paper shows how this can be done.

2. DATA COLLECTION

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 the information collected will be useful in the subsequent analysis. Data collection was conducted over a 15-month period, beginning in late March 2003 and ending in mid-June 2004. Data was collected from a total of 38 jointed plain concrete pavement (JPCP) test sites throughout the country during this period. This resulted in approximately 6,000 inertial profiler runs over 95 site visits, with more than 400,000 JCP slabs profiled.

Diurnal profiling using a high-speed inertial profiler was conducted during four periods each test day to capture the different thermal gradients present in a JCP over a daily period:

- Early Morning: maximum negative temperature gradient
- Mid-morning: approximate zero temperature gradient
- Noon: maximum positive temperature gradient
- Evening: approximate zero temperature gradient

Seasonal inertial profiler data collection was conducted during four test periods within a year, following the guidelines shown below:

- Spring: March-June
- Summer: June-September
- Fall: September-December
- Winter: December-March
- Minimum 8.3 to 11ºC (15~20ºF) difference in average ambient temperature between seasonal visits
- Minimum 2 months between seasonal visits

Quality assurance is the key for ensuring fidelity of the data collected under such a large data collection effort. Prior to commencement of data collection, quality assurance plans were developed by Transtec project team for all of the data collection tasks.

3. ANALYSIS FRAMEWORK

The analysis framework for this study was structured so that extensive pavement profile and pavement temperature data could be efficiently yet carefully analyzed to achieve the project goals. The analysis framework contains the following components:

- Isolation of Individual Slabs: A key first step is to isolate profile data for each slab by utilizing techniques such as profile synchronization and joint finding.
- Development of a Slab Curvature Algorithm: The outcome of this effort is a new slab curvature algorithm that is mechanistically sound, stable, and portable.
- Slab Curvature Analysis: All profile data collected are analyzed based on the new slab curvature algorithm.

- Slab Curvatures versus Roughness: Slab curvatures obtained from the above analysis are correlated to roughness (or more precisely, ride quality) to identify any relationship that may exist.

3.1. Isolation of Individual Slabs

A robust and effective procedure was developed to synchronize profiles prior to objective curl/warp analysis. The goal of this pre-process is to identify joint locations within profiles, thereby isolating individual slabs in order to correctly analyze the curled/warped slab shapes.

Profile synchronization was successfully accomplished by successive application of the cross-correlation process on filtered, decimated/non-decimated profiles with adjustment in sampling intervals. This process proved to very efficient and effective.

Joint identification was also accomplished 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 value was below the zero line by a threshold value. An example of a raw profile and "spike profile" is illustrated in Figure 1. The top chart is one of the many profile runs that shows dips in the elevation plot. The bottom is the resulting joint locations (indicated by "spikes") identified through the process described above.

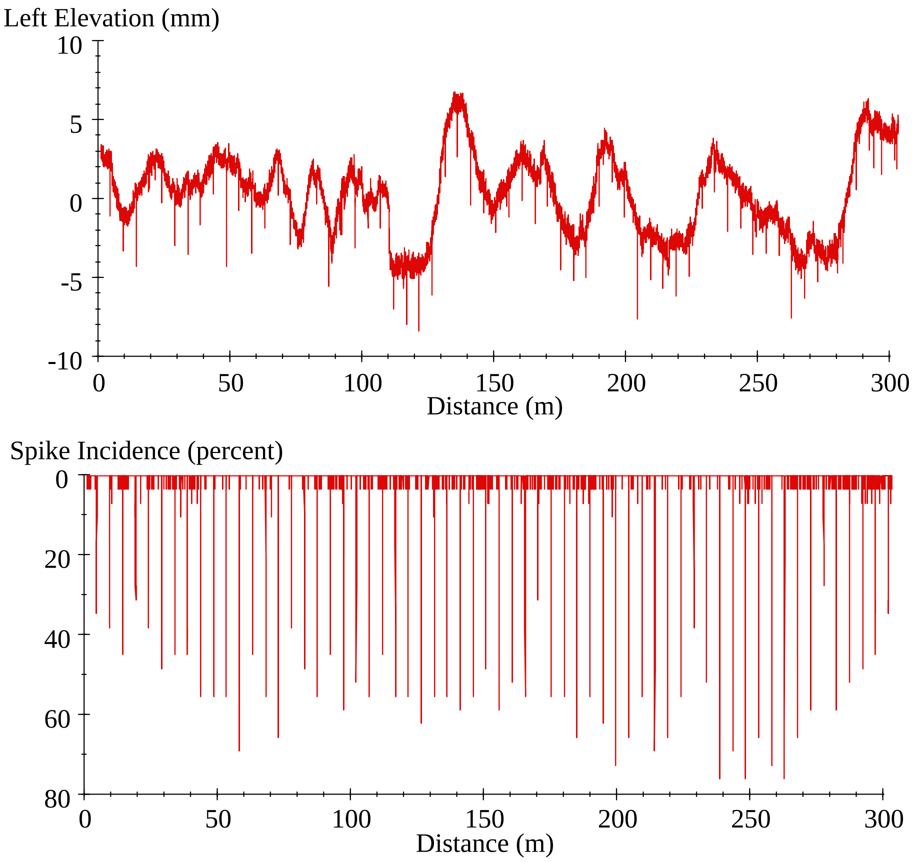

Figure 1: Raw and "spike profile" from test section 010A.

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

3.2. Development of a Second Generation Curvature Index (2GCI)

The 2GCI was developed to help overcome some of the shortcomings in terms of accuracy, stability, and portability of existing curvature indices, such as the BCI algorithm developed by Byrum et al,(1). The RMS acceleration (curvatures) index for curvature also does not appear to be a suitable index (1). Short wavelength content often dominates the calculation, amplifying both texture and artifacts of the sampling process, including the height sensor footprint, sample interval, and low-pass filter cutoff frequencies. As such, the contribution of the wavelength of interest (the slab length) is often negligible in a RMS curvature calculation. The 2GCI, on the other hand, which is based on the Westergaard curling equations (2, 3) and real-world joint restraints, seeks to better quantify slab curvature on a global level that is more representative of the slab shape as a whole.

The 2GCI adopts a global approach to derive a curvature metric that fits hypothesized slab geometries to the measured slab profile (4). Non-linear curve-fit techniques can be used to describe the shape of a slab. While almost any geometric model can be used, a Westergaard-based model is considered an appropriate selection. The resulting model parameters of the 2GCI have connection to the physical parameters that describe a jointed concrete pavement system subjected to curling and warping. Since the proposed model parameters will characterize effects beyond what Westergaard considers directly (such as slab restraint due to joint reinforcement), they are termed "pseudo-" parameters, i.e., pseudo strain gradient and pseudo radius of soil reaction. An example of such fitting is shown in Figure 2 where the "chattered" line is the detrended raw profile and the thicker, smoother blue line is the fitted line.

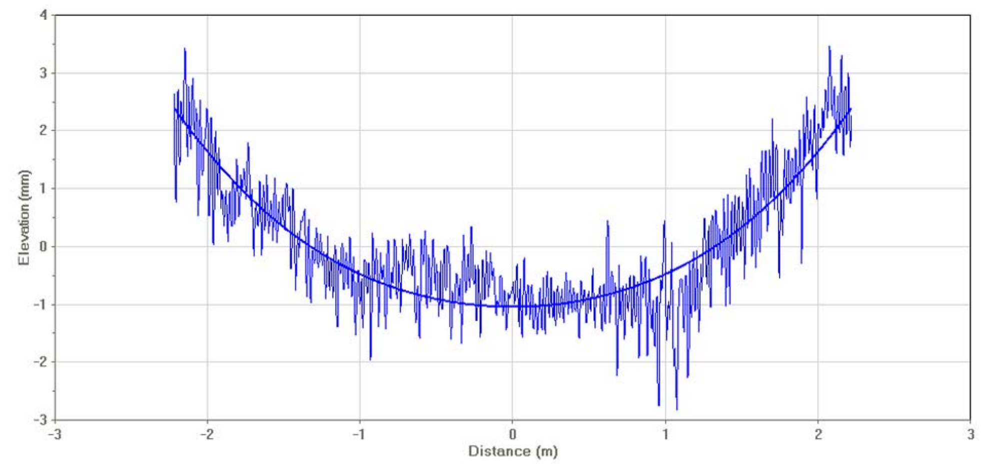

Figure 2: 2GCI Fitting

3.3. Slab Curvature Analysis

Based on extensive analyses of slab curvature from the 38 test sites under this study, the 2GCI algorithm was proven as an appropriate concept and tool to characterize slab curvature through an 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 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. Through this study, the curling pattern was found to be curled up at different levels, curled down at different levels, or even alternating in both directions.

Considering an entire site (numerous slabs) for curvature analysis, the results of this study showed that 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 from a given test period at a given site can be statistically expressed using "box plots" where the median, maximum, minimum, first quartile, and third quartiles are plotted for visualization.

This study revealed that the seasonal variation of slab curvatures (found to be 8 με/cm or less for the mean values for the project test sites) 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).

This study also showed that curvatures for adjacent traffic lanes/adjacent JCP slabs are not necessarily correlated. Corresponding slabs from both lanes may not be curled at similar levels or even the same direction. This is most likely an indication that adjacent lanes were constructed at different times.

For all the test sites examined in this study, the majority had negative mean curvature values, or a "curled up" shape. 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 calculated to be -12.6 με /cm ("curled up") and +15.7 με /cm ("curled down").

Figure 3 shows the box plot for a test section where most of the slabs are curled up (i.e., negative pseudo-gradient), while Figure 4 shows the box plot for a test section where most of the slabs are curled up (i.e., positive pseudo-gradient). Notice that the trends of diurnal curvature in the two figures are quite different. These trends give an important implication at what period in a day the pavement roughness would be the greatest.

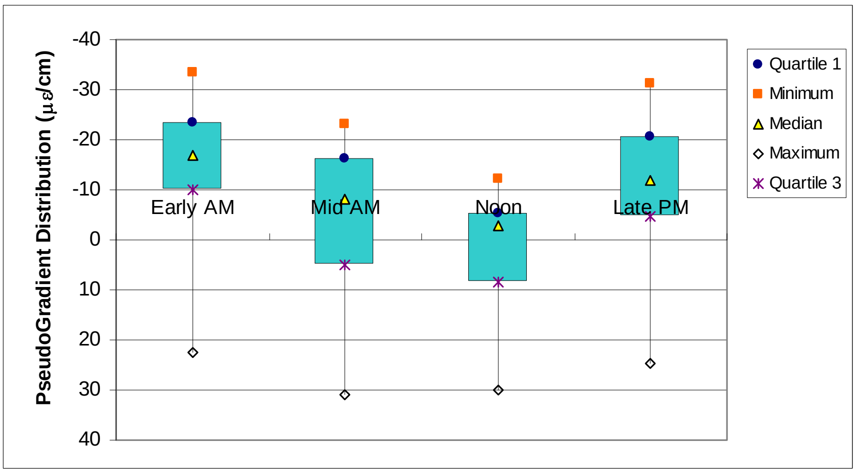

Figure 3. Diurnal curvature analysis for a "curled-up" section.

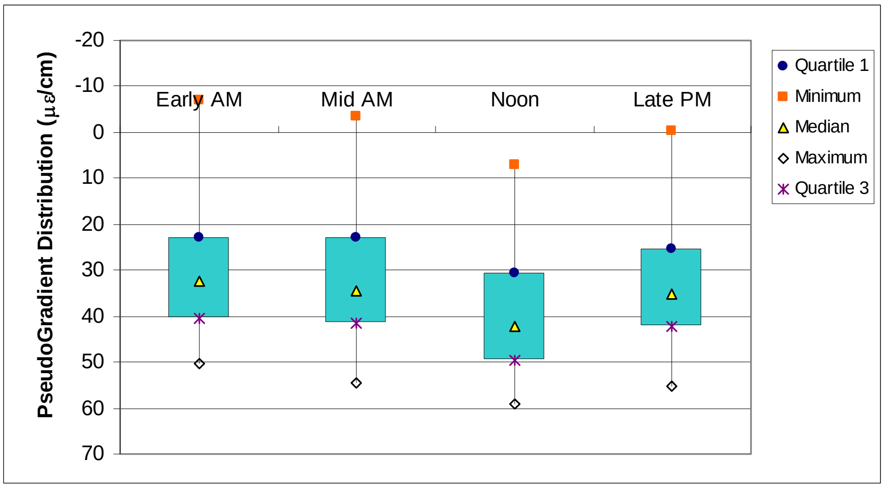

Figure 4. Diurnal curvature analysis for a "curled-down" section.

The findings from this extensive study proved the 2GCI to be an effective tool to study slab curling and warping. Studies on variability of slab curvature through a given site will not be possible without the use of this method.

3.4. Slab Curvatures versus Roughness

This comprehensive study of a wide cross-section of test sties also provided a better understanding on the impacts of slab curvatures on roughness (ride quality). A systematic approach was developed for characterizing the relationship between slab curvature and roughness through proper data collection and analysis. This approach identified five distinct categories of relationships to cover all possible site conditions and behaviors. A convenient analysis tool was also developed to facilitate visualization of the analysis and site characterization.

Based on the analysis of the sites tested under this study, it was shown that diurnal impacts of slab curling on the Half-car Roughness Index (HRI) can be as high as 0.63 m/km with an average around 0.16 m/km. This suggests that it may be prudent for more emphasis to be placed on the timing of roughness measurement within specifications, particularly for agencies working under incentive-disincentive specifications. This observation could also apply to network-level roughness measurements for 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. 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 the diurnal and seasonal effects vary significantly between sites.

An example of the correlation between slab curvature and HRI for a particular test site is shown in Figure 5. This figure shows an obvious linear relationship between the 2GCI curvature indices and roughness (HRI). Each cluster shown in the figure, corresponding to each of the seasonal runs, shows a specific range of HRIs (on the vertical scale) and 2GCIs (on the horizontal scale). The slope of the linear trend line (-0.67 m/km/(με/cm)) provides a way to quantify the impact of slab curvature on roughness. The lowest HRI values (1.02 in/mile) corresponding to the lowest upward curvature values (-5.4 με/cm) indicate that the condition when the slabs are "flattest" is when the ride quality is best. Conversely, the highest HRI values (1.63 m/km) and corresponding slab curvature (-15.2 με/cm) indicate that when the slabs are curled the most, the ride quality is worst.

When extrapolating this linear trend line to cross the y-axis (at zero curvature), the HRI at this intercept (0.59 m/km) is the theoretical HRI when the slabs are completely flat. Therefore, this HRI value at "zero curvature" could be perceived as the roughness caused by pavement features other than slab curvature. For this particular site, the slabs never reach this "flattest" condition, and are bounded by 1.63 m/km and 1.02 m/km on the HRI scale. The difference between the lowest surveyed roughness and the highest survey roughness is 0.61 m/km. The theoretical roughness at zero curvature (0.43 m/km) can then be defined as the "built-in curl" roughness.

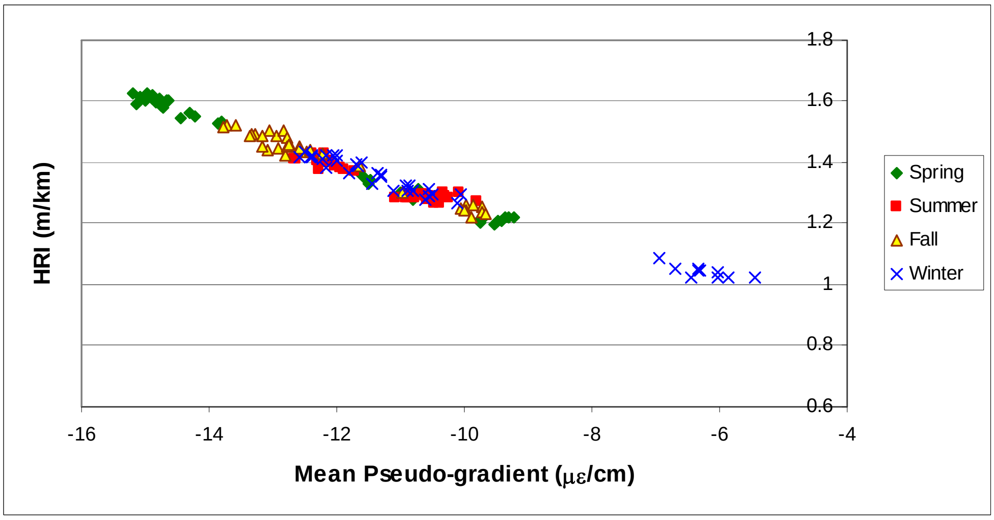

Figure 5. Roughness vs. Curvature Plot for a given test section.

The example presented above provides a visual method for evaluating the impact of slab curvature on ride quality. Based on the analyses and observations from this study, a system was established to quantitatively evaluate impacts of slab curvatures on ride quality. Once adequate (i.e., covering extreme conditions) profile data has been collected and the analysis procedures described in this report are performed, this system can produce a "signature" or specific characteristics for the curvature-roughness relationship of a given site. The analysis procedures include profile synchronization, joint identification, 2GCI curvature fitting, and roughness computation. The "extreme conditions" for profile data collection include at least two (preferably four as in this study) test periods in a given day, and testing during at least two (preferably four as in this study) seasons in a year. The effects of pavement deterioration over time are beyond the scope of this analysis, and therefore, this system will provide a "snapshot" of the condition for the surveyed year.

This system (termed "RoCK") to evaluate the impact of slab curvature on ride quality is illustrated by Figure 6. Roughness is plotted on the y-axis while the curvature is plotted on the x-axis. Negative values of curvature (i.e., negative pseudo gradients plotted to the left of the y-axis) indicate that the slabs are mostly curled up, while the positive values of curvature (plotted to the right of the y-axis) indicate the slabs are mostly curled down. It is important to note that the curvature values in this plot are mean values from each profile run for all slabs within a site, and the roughness values represent the average roughness measured by each run for the site. Plotting the roughness and mean curvature values for each run using this coordinate system often creates a "cluster" represented by the shaded area shown in Figure 6. With a basic least-square linear fit applied to this cluster, the following parameters can be computed:

- Rub: Upper Bound Roughness (the highest roughness during survey)
- Rlb: Lower Bound Roughness (the lowest roughness during survey)

- Crt: Right Bound Curvature (the extreme curvature during survey within current quadrant)
- Clf: Left Bound Curvature (the extreme curvature during survey within current quadrant)
- Src: Roughness Curvature Slope (impact of curvatures on roughness)
- Rzc: Zero-curvature Roughness (theoretical roughness value if slabs were flat)
- Rbtc: Built-in Curvature Roughness (contribution of built-in curvature to roughness)

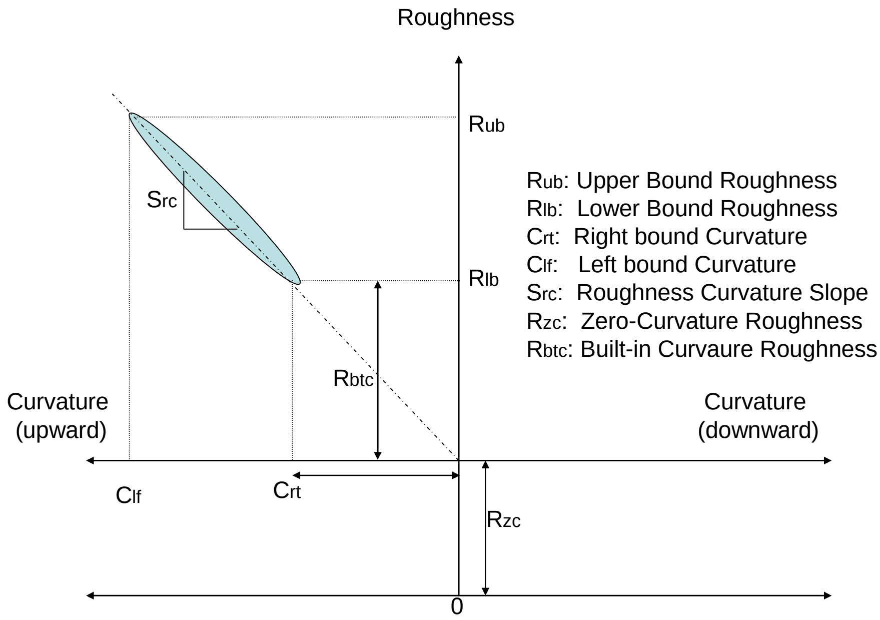

Figure 6. The RoCK diagram for Curvature-Roughness Analysis.

Based on the above parameters, a given test site can be classified based on the curvature-roughness characteristics as one of the following (illustrated in Figure 7):

- Type I-A: Slabs are curled upward significantly and curvature is a major contributor to roughness.
- Type I-B: Slabs are curled upward somewhat and curvature is not a major contributor to roughness.
- Type II: Slabs are curled both upwards and downwards and curvature is only a minor contributor to roughness.
- Type III-A: Slabs are curled downward significantly and curvature is a major contributor to roughness.
- Type III-B: Slabs are curled downward somewhat and curvature is not a major contributor to roughness.

Under this study, a comprehensive system of tools were developed and used successfully to assess diurnal and seasonal effects on ride quality. The findings and products can be used by both agencies contractors to improve smoothness specifications, pavement management systems, and construction practices to adequately factor in slab curling effects.

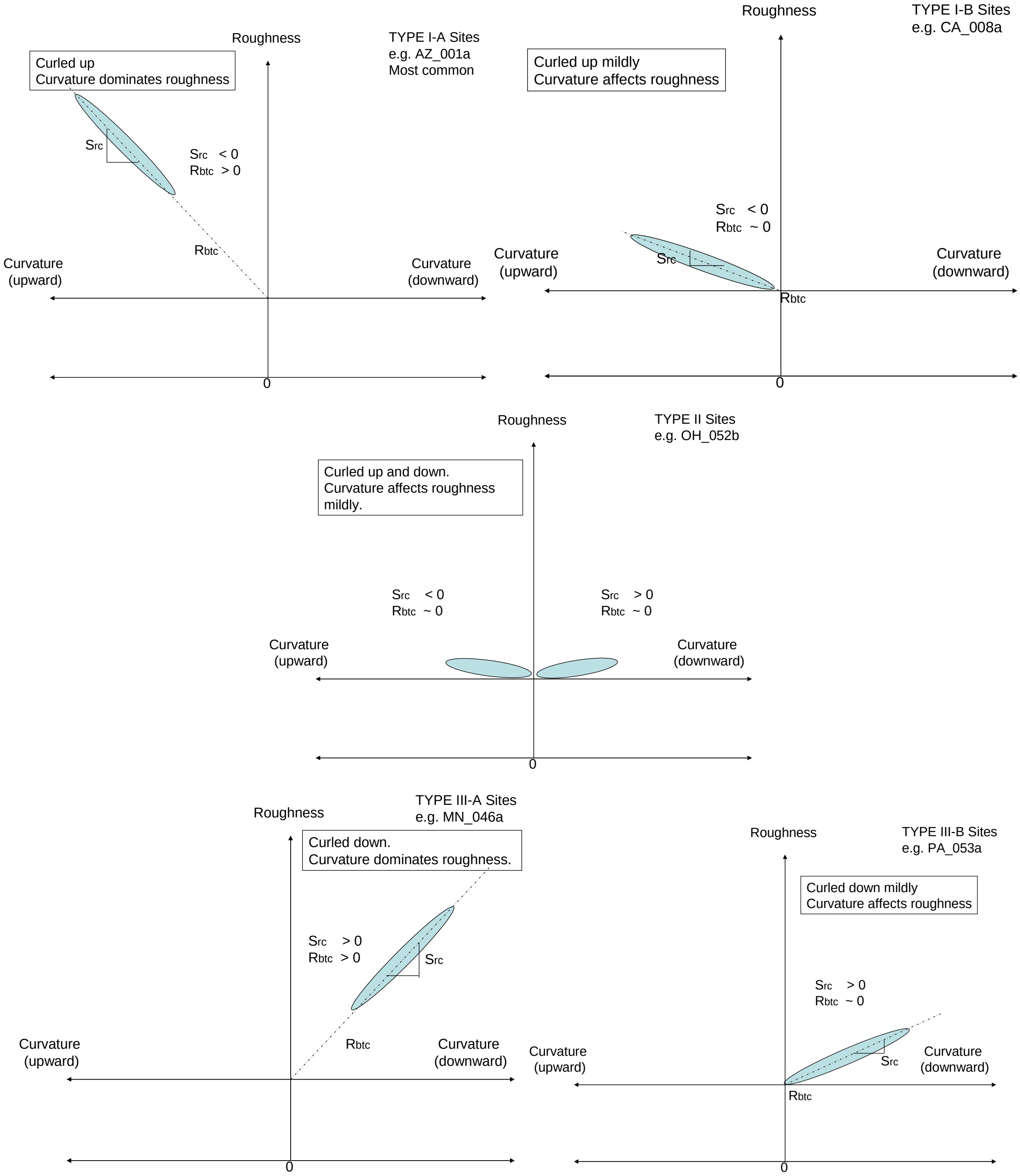

Figure 7. Various categories of slab curvature-roughness relationships.

4. CONCLUSION AND FUTURE RESEARCH

Major findings from this study can be summarized as follows:

- A procedure was developed to properly measure and characterize curling and warping of jointed concrete pavement.
- A robust method was developed to synchronize profiles and identify joint locations – a critical step for successful curvature characterization.
- A suitable metric (2GCI) based on the Westergaard curling equation was developed to quantify slab curvature.
- A system was established for quantifying the impact of curvature on JCP ride quality.

The tools developed from this study have been successfully applied to real world projects to identify causes of premature curvature-related failures of JCP (5), and to evaluate various construction practices. It is expected that there will be more extensive applications of the concepts and tools described in this paper in the future.

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