Initial smoothness of concrete pavements under environmental loads

S. Kim
Iowa State University

Halil Ceylan
Iowa State University, hceylan@iastate.edu

Kasthurirangan Gopalakrishnan
Iowa State University, rangan@iastate.edu

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Abstract
In the current paper, the effect of curling and warping, caused by environmental ambient conditions, on the initial smoothness of concrete pavements is discussed. Surface profile measurements were made during the hours of the early morning and late afternoon on an instrumented jointed plain concrete pavement (JPCP) on highway US-30 near Marshalltown, Iowa during the first seven days after construction in summer 2005. Variations in temperature and moisture during this critical period were monitored using the temperature and relative humidity sensors installed within the test sections at the time of construction. Based on the measured surface profile data, it was observed that the initial pavement smoothness, in terms of international roughness index (IRI) and the ride number (RN), was not significantly influenced by the early-age curling and warping behaviour of the JPCP. Using finite-element modelling (FEM), sensitivity studies were conducted to investigate the influence of slab curvature on initial pavement smoothness for a range of equivalent temperature differences between the top and bottom of the slab. The results indicated that the initial JPCP smoothness is sensitive to changes in slab curvature resulting from environmental ambient conditions only at higher magnitudes. Although the FEM-based IRI predictions were higher than the surface profile-based IRI values, the differences were not significant.

Disciplines
Civil and Environmental Engineering | Construction Engineering and Management

Comments
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In the current paper, the effect of curling and warping, caused by environmental ambient conditions, on the initial smoothness of concrete pavements is discussed. Surface profile measurements were made during the hours of the early morning and late afternoon on an instrumented jointed plain concrete pavement (JPCP) on highway US-30 near Marshalltown, Iowa during the first seven days after construction in summer 2005. Variations in temperature and moisture during this critical period were monitored using the temperature and relative humidity sensors installed within the test sections at the time of construction. Based on the measured surface profile data, it was observed that the initial pavement smoothness, in terms of international roughness index (IRI) and the ride number (RN), was not significantly influenced by the early-age curling and warping behaviour of the JPCP. Using finite-element modelling (FEM), sensitivity studies were conducted to investigate the influence of slab curvature on initial pavement smoothness for a range of equivalent temperature differences between the top and bottom of the slab. The results indicated that the initial JPCP smoothness is sensitive to changes in slab curvature resulting from environmental ambient conditions only at higher magnitudes. Although the FEM-based IRI predictions were higher than the surface profile-based IRI values, the differences were not significant.

Introduction

Pavement smoothness can be defined as a lack of noticeable roughness and a more optimistic view of the road condition. Pavement smoothness has been recognised as an important measurement in evaluating pavement performance because it is directly related to the serviceability of road for the travelling public. Smooth roads provide a comfortable ride, resulting in lower dynamic loads, reduced vehicle operation cost, increased safety and longer pavement life. In addition, smoother roads will have a positive effect on noise reduction owing to the motor vehicles. In particular, the initial smoothness immediately after construction can significantly affect the pavement service life. Smith et al. reported that pavements which were constructed smoother stayed smoother over time provided all other things affecting smoothness remained the same. Many agencies have established and implemented smoothness specifications for newly constructed pavements. Using these specifications, the agencies determine the bonuses or penalties to the contractor thereby encouraging the contractor to construct pavements with smoothness levels higher than a specified value.

Even though it has been recognised that higher initial smoothness can provide longer pavement life, the factors influencing the initial smoothness of a concrete pavement are not very well discussed in available literature. However, it is believed that several factors are related to the initial smoothness of a concrete pavement. These include elements related to the pavement design, material selection, concrete uniformity, climate and construction practices. The factors also include temperature and moisture variation in climate, which could result in a change in the curvature of the slab known as curling and warping.

In general, temperature differences across the depth of the concrete pavement result in curling while moisture differences result in warping behaviour. Both temperature and moisture gradients can cause either upward or downward distortion of pavement slabs, and pavement slabs are not necessarily flat at rest (i.e. they are under no external forces that cause slab distortion). Because of the self-weight of the slab and also the restraints from the shoulder or the adjacent slab as a constant load, creep that has occurred in the already deformed slab can be recovered partially over...
time.13 Jeong and Zollinger11 reported that the day-to-day trends in the slab displacement were clearly dependent upon the changes in slab temperature gradients, while the drying shrinkage and creep strains cause an overall shift in slab displacement cycle. They also observed that the slab displacement increased over time as the elastic modulus of concrete increased with time. Hveem14 is one of the first researchers to notice the effect of curling and warping on pavement smoothness measurements. Based on analysis of data collected from the long-term pavement performance (LTPP) study, Byrum15 reported that the construction condition and the complex interactions of temperature, moisture and material creep during early pavement life could result in built-in slab curling. The results of National Cooperative Highway Research Program (NCHRP) Project 10–47 also showed upward curvature in pavement profiles during a period when the temperature difference between the top and bottom of the slab was low.16

Previous studies17–20 have linked slab curling to stresses in concrete pavements. However, there is very little discussion on the effects of slab curling on smoothness and subsequently pavement life.21 Based on a number of smoothness measurements in 11 test pavements starting early in the morning to late afternoon, Karamihas21 suggested that changes in slab curvature owing to temperature variations can influence the smoothness of a concrete pavement. However, the pavements selected in the present study were at least a few years old, and therefore his findings may not apply with respect to the smoothness of a newly constructed pavement, which is an important quality control factor for deciding the payment for a contractor. For instance, Perera et al.22 observed that there was no noticeable effect of slab curvature changes affecting the smoothness in five newly constructed pavements.

The current study was conducted to investigate the effect of slab curvature resulting from environmental loading on the initial smoothness of concrete pavements. Surface profile measurements were conducted during the early morning and late afternoon in 267 mm (10.5 in.) thick jointed plain concrete pavements (JPCPs) near Marshalltown, Iowa during the first seven days after construction in the summer of 2005. Temperature and humidity variations in the pavement sections were also monitored. Based on finite-element modelling (FEM)-generated slab curvature profiles, sensitivity analyses were conducted to investigate the influence of temperature variations on initial smoothness over a wide range of temperature differences that could not be observed in the tested pavements. The procedure and the results of data analysis are discussed in this paper, highlighting the important findings regarding the effect of slab curvature resulting from environmental loading on the smoothness of newly constructed pavements at the critical time immediately following construction.

Roughness index

Since pavement smoothness is related to a lack of roughness, the severity of roughness in pavements has been used to characterise the smoothness. Several roughness indices representing the severity of roughness have been developed. Among them, the three most common roughness indices currently used in many agencies are the international roughness index (IRI), ride number (RN) and profile index (PI).2,23

The World Bank initiated the development of IRI based on the findings of a correlation experiment conducted in Brazil so that all roughness-measuring instruments in use throughout the world could produce measures on a common scale, and then establish IRI as that scale.24 The computation of IRI is based on a mathematical model simulating the vehicle dynamic response to a measured pavement profile.24 Considering the complications involved in modelling the IRI, the IRI is typically computed in specially designed computer programs based on the measured pavement profiles.

The RN was developed to simulate the subjective rating of expert panel members regarding the road roughness based on the pavement profile data.25,26 A true pavement profile filtered using specific procedures is summarised as a statistic value such as the root-mean-square (RMS). This RMS is transformed to RN ranging from 5 (perfectly smooth) to 0 (the maximum possible roughness) with a non-linear statistical equation. Like IRI, the computation of RN can be conducted by a computer program. RN is more sensitive to shorter wavelengths in pavement profile than the IRI. Thus, RN is correlated to IRI but the two are not interchangeable and each parameter provides unique information about the roughness of the pavement.2

Since the time California-type profilograph has been used for measuring the smoothness of newly constructed pavements, many agencies have used the PI parameter. The PI is the accumulated deviations beyond some specific blanking bands drawn on a recorded pavement trace with profilograph. It should be noted that each agency follows its own standard procedure for determining the PI because of the absence of a universal standard for the application of a specific blanking band such as 0, 2.5 and 5 mm.5

Currently, most state agencies use the PI for judging the quality of new pavements and a profile statistic such as IRI for monitoring the condition of their pavement network.5,23 In this case, it is difficult to relate the smoothness of the pavement at some point in time with its initial smoothness. The newly released Mechanistic-Empirical Pavement Design Guide (MEPDG) under NCHRP Project 1–37A incorporates IRI prediction models that include the initial IRI as an input parameter.27 Thus, many agencies are trying to establish IRI as the future smoothness index for the acceptance of new pavements.23
Test section and data collection

Profile measurements were conducted on 267 mm (10.5 in.) thick JPCP slabs on an open-graded granular base in highway US-30 near Marshalltown, Iowa. The transverse joint spacing was approximately 6 m (20 ft). The passing lane was approximately 3.7 m (12 ft) in width, and the travel lane was approximately 4.3 m (14 ft) in width. A hot-mix asphalt (HMA) shoulder was added approximately two months after initial construction. The cement content and the water:cement ratio of paved concrete was 266 kg/m³ and 0.4, respectively. The powder-type curing compounds were sprayed on slabs during the early cure period but no protection against wind was applied in test sections. A more detailed description of the design and construction of test sections is described by Kim.28

The travel lanes in two test sections, as shown in Fig. 1, correspond to morning and afternoon construction selected for profile measurements. An International Cybernetics Corporation Rollingprofiler1 29 was used for surface profile measurements at different times (morning and the afternoon) along the different traces of longitudinal direction in test sections to obtain an RI such as IRI or RN. The temperature and humidity variations were monitored during profiling measurements. These profile measurements in a diurnal cycle for the same location could provide a better understanding of the effect of the slab curling and warping on the smoothness. In addition, four individual slabs in each test section were selected for identifying the slab deformation owing to environmental loading with the Rollingprofiler1. The Rollingprofiler1 measured surface profiles following the diagonal and transverse traces in each slab. The slab curvature profiles, shown in Fig. 2, were obtained from the measured surface profiles after removing the noise based on a similar procedure suggested by Sixbey et al.30 and Vandenbossche.31

The variations in slab deformation were influenced not only by temperature differences but also by moisture differences between the top and the bottom of the Portland cement concrete (PCC) slab. The temperature and humidity sensors installed within the test sections detected the temperature and moisture variations. Slab temperature and moisture data were collected at 5 min intervals throughout the field evaluation periods. Temperature instrumentation consisted of seven temperature sensors attached to a stake at different depths below

![Fig. 1. Test section instrumentation and profile measurement layout: (a) test section 1: afternoon paving (13 July 2005); (b) test section 2: morning paving (14 July 2005)](image_url)
surface and placed 0.9 m (3 ft) from the pavement edge before the paving started. Humidity instrumentation consisted of four moisture sensors inserted into small polyvinyl chloride (PVC) pipes, which were placed side by side at different depths from the pavement surface to measure the humidity variation in the slab.

The variations in temperature and moisture differences with time are plotted in Fig. 3. In general, temperature differences are positive during daytime and early night-time and negative during late night-time and early morning. In contrast, moisture differences presented as ‘RH diff’ in Fig. 3 show the reverse trend. Especially during day 0 and day 1 of paving, moisture differences are negative for the most part—that is, higher moisture at the bottom of the slab compared with the top. This indicates higher drying shrinkage of concrete near the top of the slab causing the slab corner to warp upwards during day 0 and day 1 of paving.

Profile data analysis

The raw data measured with Rollingprofiler indicated the differences in elevation between the supports

Fig. 2. JPCP slab curvature profile

Fig. 3. Temperature and moisture differences between top and bottom of JPCP slab with time
along the line being profiled.\textsuperscript{29} Even though the raw data can give some indication of the pavement roughness based on the measured elevation differences on the pavement surface, it is necessary to transform these data to a roughness index such as IRI or RN. The pavement profile viewing and analysis (ProVAL) software (version 2.5) was used to compute IRI and RN from the measured raw data. This software is a product of Federal Highway Administration (FHWA) research efforts and it allows the user to view and analyse pavement profile in many different ways.\textsuperscript{32,33}

Figure 4 shows the variation in IRI and temperature differences of two test sections during the days on which profile measurements were conducted. Since RN ranges from 5 (perfectly smooth) to 0 (the maximum possible roughness), the variations in RN values are

![Graph](image-url)

**Fig. 4. Variations in IRI during first seven days after paving: (a) test section 1: afternoon paving; (b) test section 2: morning paving**

*Magazine of Concrete Research, 2007, 59, No. 8*
presented separately in Fig. 5. The temperature differences varied from $-6.5^\circ C (-11.8^\circ F)$ to $8.5^\circ C (15.3^\circ F)$ during the experimental periods.

Test section 2, which was paved in the morning, shows higher smoothness compared with test section 1, which was paved in the afternoon. The differences in IRI and RN between the two sections are nearly 528 mm/km (33.5 in./mile) and 0.4, respectively. In addition, there are variations with respect to measurement locations in test sections 1 and 2. The maximum differences in IRI and RN values considering different measurement locations are 466 mm/km (29.6 in./mile) and 0.7 for test section 1, and 432 mm/km (27.4 in./mile) and 0.5 in test section 2. However, the measured IRI

![Variations in RN during first 7 days after paving: (a) test section 1: afternoon paving; (b) test section 2: morning paving](image-url)
and RN in both the test sections were not considerably influenced by variations in temperature differences, as seen in Figs 4 and 5. These observations strongly suggest that the slab deflection caused by temperature variations in these test sections did not influence the pavement smoothness. This is in agreement with the results reported by previous research studies.22

FEM simulation for deflection response to environmental loads

Even though the field-measured IRI and RN did not seem to have much influence on the slab deformation owing to environmental loads, it still cannot be concluded that the slab curvature has no influence on the initial smoothness because the range of measured temperature differences is quite narrow. Finite-element (FE) models using ISLAB 2000 (two-dimensional (2D) FE model) and EverFE 2.24 (three-dimensional (3D) FE model) were built for modelling the test sections in this study to investigate the effect of environmental loading on smoothness. The models were built with the actual geometric proportions and material properties from the test sections. Even though the slab temperature profiles with depth have long been characterised as non-linear distributions, the observed temperature profile in the present study showed nearly a linear temperature distribution. Additionally, it has been reported that the non-linear component of the slab temperature distribution does not influence the deflections very much.12 Therefore, a linear temperature distribution was used in the FE modelling (FEM) to investigate slab deflections in this study. Although this assumption is not strictly valid, it makes the design conservative and simple.34

Preliminary analyses of the pavement systems using the ISLAB 2000 and EverFE 2-24 software with appropriate material property inputs and non-linear temperature distributions indicated that the FEM results could not generate the effect of permanent upward curling and warping measured in the field—that is, the field-measured slab shape at maximum positive temperature difference in 7 days was almost flat while the FEM-generated slab shape showed downward curling at the same temperature difference. This may be because of the permanent curling and warping at zero temperature difference owing to differential irrecoverable shrinkage or a positive temperature difference during setting of the concrete.12,13,35-37 When the pavement temperature difference reaches some amount of positive value after the hardening of concrete, the permanent curling and warping are removed so that the slab tends to flatten. Thus, the permanent curling and warping could be considered as the deformation associated with the negative value of a positive temperature difference making the slab flat. This is defined in the MEPDG27 as the effective permanent curling and warping temperature difference.12 In the current study, a maximum positive temperature difference of 8.5°C (15.3°F) during evaluation periods was assumed for maintaining a flat-slab condition (for a 267 mm thick slab) since the measured slab curvature profiles show upward curl at negative temperature differences and maintain almost a flat shape at positive temperature differences. This temperature difference is similar in magnitude to those that have been reported by other researchers.27,35,38 In the present study, the equivalent temperature difference, associated with the actual pavement behaviour, was defined as the sum of the measured temperature difference and the effective permanent curling and warping temperature difference.

Comparisons between the field-measured slab curvature profiles and the FE-computed slab curvature profiles were undertaken. The measured slab curvature profiles following diagonal and transverse traces were obtained from four individual slabs in each test section (see Fig. 1 for slab locations). The predicted slab curvature profiles at the equivalent (positive and negative) temperature differences at which pavement profiles were measured were computed by the FE programs.

A total of 44 field profiling measurements and the corresponding FE-predicted profiles were obtained during the field evaluation periods. The measured and predicted slab curvature profiles along the diagonal direction at the equivalent temperature difference 3 days after paving are compared in Figs 6 and 7 for the sake of illustration. In general, the comparisons showed that the FE-predicted slab curvature profiles are in good agreement with the measured slab deflection profiles.

FEM-based sensitivity analysis of smoothness index

Using the FEM models, sensitivity analyses of IRI and RN values were conducted at different equivalent
temperature differences in each measured location. This approach has been previously used by Siddique and Hossain. Since the JPCP is a combination of several slabs, the same slab deflection profile could be repeated in each slab to form a continuous deflection profile, provided that all of the material properties, the geometry and the applied environmental loading of these slabs are same. Fig. 8 displays such continuous slab deflection profiles for the test sections resulting from different equivalent temperature differences.

The IRI and RN values were calculated from these continuous deflection profiles generated by EverFE 2.24 and ISLAB 2000 at different equivalent temperature differences. The IRI and RN values were calculated for each measured location, respectively, and were found to be very similar. Therefore, the average IRI and average RN values for all measured locations are displayed in Figs 9 and 10.

Since the FE-generated slab deflection profiles were influenced by only the equivalent temperature differences, the computed IRI and RN values will reflect the effect of environmental loading. The computed IRI values increased with respect to changes in equivalent temperature differences, while the calculated RN values decreased. The IRI values obtained using EverFE 2.24 were similar for both positive and negative equivalent temperature differences. Using ISLAB 2000, the IRI values associated with the negative equivalent temperature differences were higher than those obtained at the positive equivalent temperature differences. The maximum IRI values associated with the maximum equivalent temperature differences (−13°C and 13°C) were 216 mm/km for EverFE 2.24. Using ISLAB 2000, the IRI was 334 mm/km for the maximum positive equivalent temperature difference condition (13°C) and 448 mm/km for the maximum negative temperature difference condition (−13°C). The RN values varied within a narrow range of 4-6 to 5-0 for the range of equivalent temperature differences considered in the current study.

Although it can be observed that the deflection resulting from environmental loading can influence the JPCP smoothness in terms of IRI and RN in limited equivalent temperature difference ranges, it is necessary
to compare these results with the smoothness specification of new concrete pavements used by state highway agencies to investigate if this smoothness variation is significant. According to typical IRI specifications, the difference in IRI value from the bonus range to correction range is approximately 631 mm/km.

Comparison of measured and FEM-predicted smoothness indices

The field-measured smoothness index included all surface behaviours such as surface irregularities, constructed slopes and slab deflections while the FEM-predicted smoothness index included only slab deformation owing to environmental loading. In the current study, the change in smoothness index value between positive temperature difference and negative temperature difference was selected for making comparisons. Because the profile measurements were made during diurnal cycles for the same location, the change in field-measured IRI values and RN values between the positive and negative temperature conditions could only be influenced by slab deflection owing to environmental loading. The change of FEM-predicted IRI values and RN values corresponding with the change in field-measured RI values can be obtained from Figs 9 and 10. The results are compared and summarised in Table 1.

From Table 1 the changes in IRI and RN values predicted by both the FEM programs are higher than the field-measured values. The differences between the field-measured values and FE-predicted values may be attributed to a number of factors. The assumptions used in the FE model for simplifying the actual field condition could be ascribed to this difference. Apart from the environmental loading, the field measurements are also influenced by interactions of environmental loading such as the moisture variation and creep behaviour to temperature loading. Although the FEM-predicted IRI was calibrated to reflect the effect of the permanent built-in curling and warping, it cannot include all the effects resulting from the moisture variation and creep behaviour. The moisture variation owing to daily weather variation and the creep behaviour of the slab can lead to recovery of slab deformation resulting from temperature loading thus reducing the difference in IRI between positive and negative temperature conditions. The movement of the pavement foundation (any differential heave and differential settlement of the pavement subgrade) is also something that was not included in the FE modelling of the rigid pavement systems analysed in the current study.

However, in a study conducted by Smith et al. which established the equivalent IRI value corresponding to PI-based smoothness specifications, it was shown that the standard error of the equivalent IRI values ranged from 264 mm/km to 316 mm/km considering the PI-based specifications used by different agencies. Thus, in the context of findings reported by Smith et al., the differences between FEM-predicted and measured IRI values in this study are not significant.

Conclusions

The present study investigated the effect of slab curvature owing to environmental ambient conditions on the concrete pavement initial smoothness. Based on the results of this study, the following observations were drawn.

(a) The measured IRI and RN values were different at different measurement locations within a test section.

Table 1. Comparison between changes of measured and FEM-predicted roughness index for different temperature conditions

<table>
<thead>
<tr>
<th>Test section</th>
<th>Location</th>
<th>Changes of IRI</th>
<th></th>
<th>Changes of RN</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured: mm/km</td>
<td>Predicted with EverFE 2.24: mm/km</td>
<td>Predicted with ISLAB 2000: mm/km</td>
<td>Measured</td>
</tr>
<tr>
<td>Section 1</td>
<td>Edge</td>
<td>0.0</td>
<td>160.7</td>
<td>365.9</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>0.6 m from shoulder</td>
<td>3.2</td>
<td>164.7</td>
<td>355.0</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>0.9 m from shoulder</td>
<td>20.5</td>
<td>181.7</td>
<td>381.5</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Centre</td>
<td>13.5</td>
<td>171.0</td>
<td>329.6</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>0.9 m from vertical joint</td>
<td>37.9</td>
<td>197.8</td>
<td>423.4</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>0.3 m from vertical joint</td>
<td>50.0</td>
<td>181.0</td>
<td>387.3</td>
<td>0.01</td>
</tr>
<tr>
<td>Section 2</td>
<td>Edge</td>
<td>45.5</td>
<td>132.9</td>
<td>308.3</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>0.6 m from shoulder</td>
<td>7.7</td>
<td>145.1</td>
<td>324.4</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>0.9 m from shoulder</td>
<td>1.3</td>
<td>135.1</td>
<td>285.2</td>
<td>0.04</td>
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<td></td>
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<td>143.0</td>
<td>280.7</td>
<td>0.01</td>
</tr>
<tr>
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<td>0.9 m from vertical joint</td>
<td>27.0</td>
<td>122.1</td>
<td>242.6</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>0.3 m from vertical joint</td>
<td>16.1</td>
<td>121.0</td>
<td>248.5</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Magazine of Concrete Research, 2007, 59, No. 8
The measured IRI and RN were not considerably influenced by the limited range of temperature differences considered in this study.

Based on the limited field data, it appears that morning paving produces smoother JPCP pavements (in terms of measured smoothness indices) compared with afternoon paving.

The IRI and RN differences (between the positive and negative temperature conditions) predicted by both the 2D and 3D FEM programs overestimate the field-measured counterparts. However, the difference between the FEM-predicted IRI and measured IRI may not be significant, considering the range of specifications used by different transportation agencies.

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Magazine of Concrete Research, 2007, 59, No. 8


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Magazine of Concrete Research, 2007, 59, No. 8 609