Impact of Slab Curling on Backcalculation Analysis

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Abstract

Falling Weight Deflectometer (FWD) testing is performed on rigid pavements to assess the in-situ structural capacity of the pavement system, to evaluate the load transfer efficiency across transverse joints/cracks and to identify joints with high possibility of voids underneath the slabs. Tests are performed at different times of the day (day and night), different seasons and different temperature conditions. This data is used in the analysis to identify the network needs and prioritize these needs considering budget and performance constraints. One key issue in this process is that FWD data collected under different environmental conditions is compared and decisions are made based on the comparison results. Therefore, an effort should be made to minimize the impact of the difference in environmental conditions during FWD testing on the final analysis results.

Decisions, such as repair joints having low load transfer efficiency, underseal joints with voids, or repair slabs with low structural capacity, are made based on analysis of results of FWD testing that was performed under different temperature and moisture conditions. A classic example of temperature impact on Maintenance & Rehabilitation (M&R) decision is corner curling, which may be identified mistakenly as potential void. Undersealing the joint in this case may cause more harm to the slab. Another classic example is the artificial high load transfer observed when FWD tests are performed at high ambient temperatures (>80^{o}F). Therefore, it is essential to make sure that the difference in temperature and moisture conditions do not have a significant impact on the FWD analysis results to avoid making inaccurate decisions at the network and project levels.

This paper presents an effort to account for the impact of daily temperature variation on FWD analysis results for rigid pavements. The work presented in this paper is a part of a large-scale research study sponsored by the New Jersey Department of Transportation (NJDOT) to study the seasonal variation in pavement properties and its impact on pavement response and performance.

Introduction

Stresses in rigid pavements result from traffic loads, as well as from environmental factors. Cyclic changes in temperature and moisture are among the environmental factors that influence rigid pavement response to traffic loads, and hence its performance. Portland Cement Concrete (PCC) slabs are subjected to a

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temperature and moisture gradient through the depth, which cause the edges and corners of the slab to undergo an upward and downward movement. For example, when the slab surface is cooler than its bottom, the slab tends to curl upwards and vice versa. The amount of actual slab curling is a function of several factors, which include slab dimensions, thickness, dowel and tie bars, shoulder type, and temperature gradient.

In addition to the internal stresses that develop when the slab weight resists the curling movements, slab curling may be confused with voids under the slab corners. Void detection is done by performing deflection testing using FWD. FWD testing is performed at different slab positions, mid-slab, joint approach and leave, and corners. Mid-slab deflections are used to back calculate the PCC layer modulus (E_{pcc}) and the modulus of the subgrade reaction (k) of the PCC slab foundation. Joint approach and leave deflections are used to evaluate the Load Transfer Efficiency (LTE) across transverse joints. Corner deflections are used in conjunction with other deflections to identify voids under the PCC slabs. There are several procedures that are commonly used for void detection analysis. Comparing the corner deflections with joint deflections is among these procedures. However, one may mistakenly identify a curled slab as if it has voids.

FWD testing can be performed at the network level for planning purposes, as a part of the Pavement Management System (PMS) program, and/or at the project level to select the appropriate Maintenance and Rehabilitation (M&R) activities. The testing protocol is similar in both cases with the exception of the testing frequency, more joints and slabs are tested at the project level. FWD testing for rigid pavements is time consuming compared with that for asphalt pavements because testing has to be performed on different slab positions (mid-slab, joint approach, joint leave, and corner).

At the network level, testing is performed on different parts of the highway network over a few years cycle to come up with an assessment of the structural condition of the network. Although FWD testing at the project level is typically done within a few days, the temperature changes within one day may vary significantly enough to impact the analysis results. Also, the outcome of the FWD analysis at the project level is expected to be more accurate.

Backcalculation analysis is performed on mid-deflections to determine E_{pcc} and modulus of subgrade reaction (k) of the slab foundation. In this analysis, the area of the deflection basin is used along with the maximum deflection and slab thickness for this purpose as suggested in 1993 AASHTO Design Guide (1). This procedure assumes that the mid-slab is in full contact with the foundation. However, this assumption has to be validated during the field-testing. Does slab curling have any impact on the backcalculated E_{pcc}? And if curling has an impact on the results, is this impact significant? How does the curling phenomenon be addressed in FWD testing and analysis? These questions have not been answered or adequately addressed yet. This paper presents an effort towards answering some of these important questions. Research Significance

Papers must address the significance of the work to researchers and/or practitioners, either in the abstract or introduction or in a separate section on “Research Significance.”

Background

In early 2001, the NJDOT initiated a study to investigate the seasonal variation of pavement materials and its impact on pavement response and performance. One of the study objectives is to evaluate and calibrate some of the available seasonal and temperature adjustment models, or to develop new models, to suit New Jersey conditions. These models will be used in the network-and-project level FWD analyses and will be ultimately incorporated in NJDOT pavement design procedure.

As a part of this study, several flexible, rigid and composite pavement test sections are instrumented with temperature probes (Thermometers), moisture probes (TDR's), frost penetration probes (resistivity probe) and ground water depth probe (vibrating wire). In addition, weather stations are installed to monitor air temperature and rainfall. Two rigid pavement sections are included in the study, which are sections S5 and S6. S5 has 9.75" PCC slab on top of a 4" limestone aggregate base course and 8" sandy gravel subbase on top of a sandy loam subgrade. S6 has 10.00" PCC slab on top of a 3" crushed aggregate base course and 34" sandy gravel subbase on top of a clayey silt subgrade. S5 has an AC shoulder, while S6 has a gravel shoulder.

Deflection testing using FWD and seismic testing using the Seismic Pavement Analyzer (SPA) are performed on monthly basis, and bi-weekly during recovery periods. The tests are performed on pre-selected and marked locations within each test section. The test locations for rigid pavements include mid-slab, wheel paths, edge, corners, and the approach and leave sides of transverse joints and cracks within the test section. In total, S5 (2) has 20 different test locations, while S6 (3) has 22 test locations.

In addition to the regular testing, two, 24-hour testing cycles were performed on one of the rigid pavement test sections included in the study (November 2002 and April 2003). In this testing cycle, FWD and SPA tests were repeated on the pre-selected locations every 2 hours. The purpose of this testing was to capture the impact of the short term temperature cycles (daily cycles) on the PCC response.

Several data quality checks were performed on the collected deflection data and environmental data to ensure that only accurate data is used in this study to develop the required models. Data that passed the quality checks was stored in the study database for further analysis. The standard 1993 AASHTO (1) backcalculation analysis was performed on the deflection data that is stored in the database. Results of the analysis were then reviewed as a part of the project quality assurance plan.

Results of the 24-hour Testing

Figures 1 and 2 show the results of the November 2002 and April 2003 24-hour testing cycles. In these figures, the measured ambient temperature distributions, along with the deflection at different test positions (mid-slab, corner, etc.) are shown for the November 2002 and April 2003 testing cycles, respectively. As can be seen, the ambient temperature for the November and April cycles ranged from 1^oC to 11^oC and from 12^oC to 22^oC, respectively.

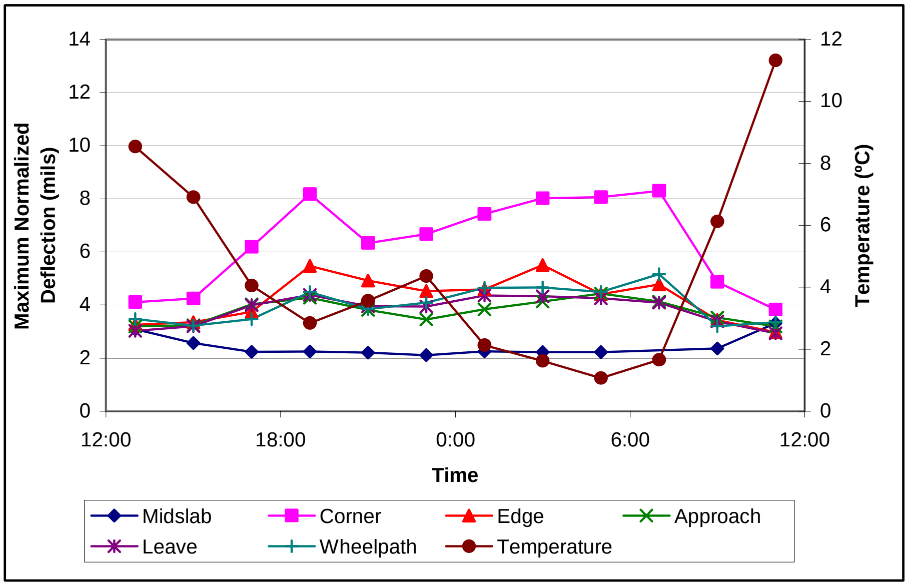


FIGURE 1 Ambient Temperature and Measured Deflections during the November 2002 Cycle.

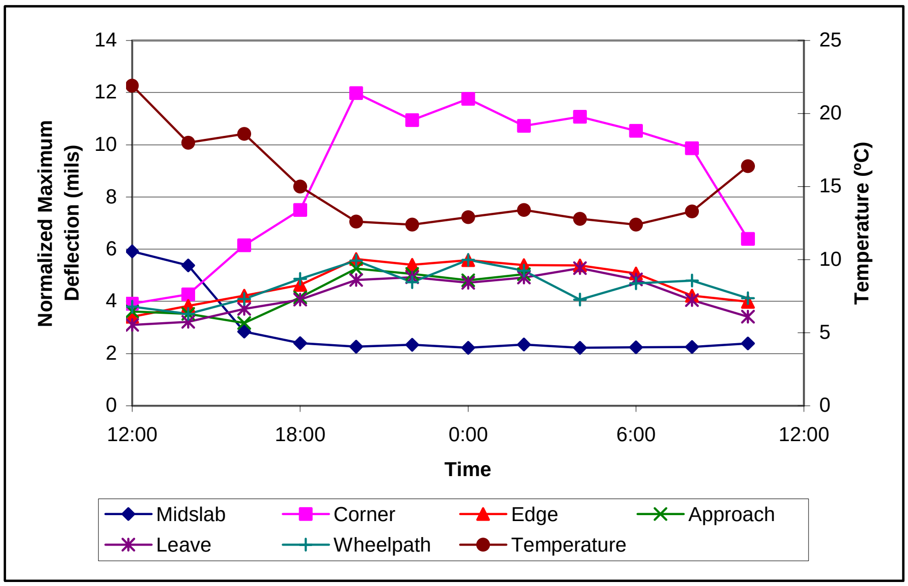


FIGURE 2 Ambient Temperature and Measured Deflections during the April 2003 Cycle.

As a result, the deflections measured at different slab positions changed as follows:

- November 2002 Cycle
  - Mid-slab deflections changed by 57% on average
  - Edge deflections changed by 85% on average
  - Wheel path deflections changed by 61% on average
  - Joint deflections changed by 44% on average
  - Corner deflections changed by 117% on average
- April 2003 Cycle
  - Mid-slab deflections changed by 167% on average
  - Edge deflections changed by 64% on average
  - Wheel path deflections changed by 59% on average
  - Joint deflections changed by 68% on average
  - Corner deflections changed by 206% on average

As can be seen, in general the observed deflection pattern at all slab positions followed the measured ambient temperature trend. However, the corner deflection is found to be the most sensitive deflection for temperature changes, while the mid-slab deflection was the least sensitive to temperature changes.

Figures 3 and 4 show some of the backcalculation results for the November 2002 and April 2003 testing cycles. Figure 3 shows E_{pcc} and k, which are backcalculated from the wheel path deflections; while the LTE was calculated from the joint approach and joint leave deflections as shown in Figure 4.

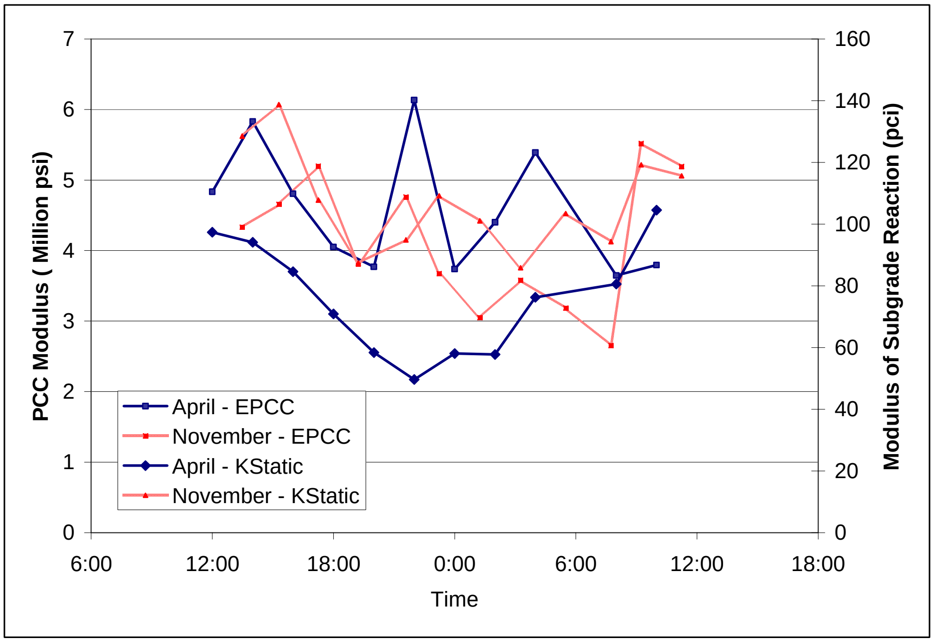


FIGURE 3 Backcalculated Slab Modulus (E_{pcc}) and Subgrade Modulus (k) (November and April Cycles).

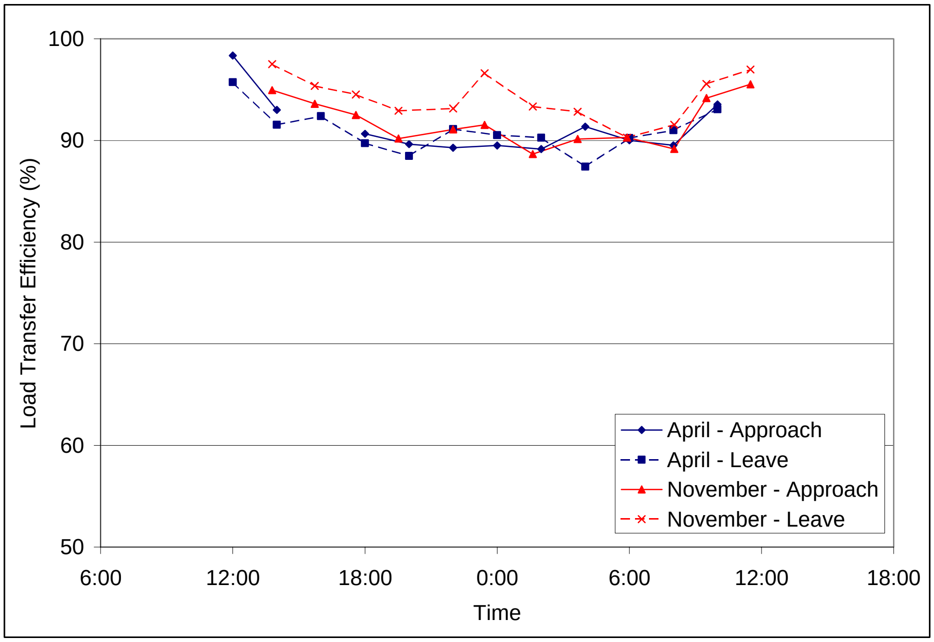


FIGURE 4 Load Transfer Efficiency (November and April Testing Cycles).

The following are the observed changes in E_{pcc} and k during the November and April testing cycles:

- November 2002 Cycle
  - E_{pcc} ranged from 2.65 to 5.5 million psi (the maximum is 207% of the minimum value)
  - k ranged from 86 to 139 pci (the maximum is 162% of the minimum value)
  - LTE ranged from 88% to 97%
- April 2003 Cycle
  - E_{pcc} ranged from 3.65 to 6.1 million psi (the maximum is 167% of the minimum value)
  - k ranged from 50 to 105 pci (the maximum is 210% of the minimum value)
  - LTE ranged from 87% to 98%

It should be noted that the timing of the observed maximum and minimum E_{pcc} did not match any of the maximum or the minimum k values for both cycles. As can be seen, a very significant change in E_{pcc} and k values is observed for both cycles. On the other hand LTE values did not show any significant change.

Analysis of the Results

During the review of the backcalculation analysis results of the November, 2002 cycle, it was found that the E_{pcc} modulus, backcalculated from either the wheel path deflections or from the mid-slab deflections significantly increased within 2 hours. This triggered more investigation to ensure that no error was made in the process. All collected data was carefully reviewed, including the raw deflection data. The ambient temperature for the November 2002 testing cycle ranged from 1°C to

11^{o}C within the testing period (24 hours). The maximum deflection measured at the right wheel path ranged from 3.2 mils to 5.3 mils (65% change) during the testing period, while the mid-slab maximum deflection ranged from 1.9 mils to 3.4 mils (75% change) during the testing period. This change happened within 2 hours only. It should be noted that there was a 2-hour lag between the increase in the wheel path deflection and that of the mid-slab deflection. The wheel path deflection started the rapid change at 7:00 AM, while the mid-slab deflection started the rapid change at 9:00 AM. As a result, the backcalculated E_{pcc} almost doubled within this 2-hour period.

During the time between 7:00 AM to 9:00 AM, the air temperature had its steepest change (4.6^{o}C per hour). Since this significant change in deflection happened during that time, slab curling is the most possible reason for it. A reasonable explanation for this significant change in deflection within this short period is that the slab changed its curvature shape. Since the ambient temperature rapidly increased, the top of the slab is expected to expand at high rate. If the slab was flat, then it is expected that the slab center will curl upward. This will result in higher wheel path and mid-slab deflection and lower edge deflection. However, the observed pattern was the reverse of that. It was observed that both wheel path and edge deflections decreased; and there was no significant change to the mid-slab. Therefore, it is expected that the slab was in upward curling mode, mid-slab was down fully supported, and slab corners were upward curling. When the ambient temperature increased, the slab top started to expand and the slab started to be flat, as shown in Figure 5. To confirm this explanation, the mid-slab deflection was reviewed, as shown in Figure 1. As can be seen, the mid-slab deflection was at its lower value, i.e. fully supported mid-slab, from 5:00 PM to 9:00 AM. After this period, the mid-slab started to curl upward and the measured mid-slab deflection started to increase, which is in agreement with the given explanation. The deflection contours of different slab positions were plotted and presented in Figure 6. As can be seen from this figure, the mid-slab at 5:00 AM showed the same deflection value as that measured at 9:00 AM. On the other hand, the edge and wheel path deflections measured at 5:00 AM are higher than those measured at 9:00 AM.

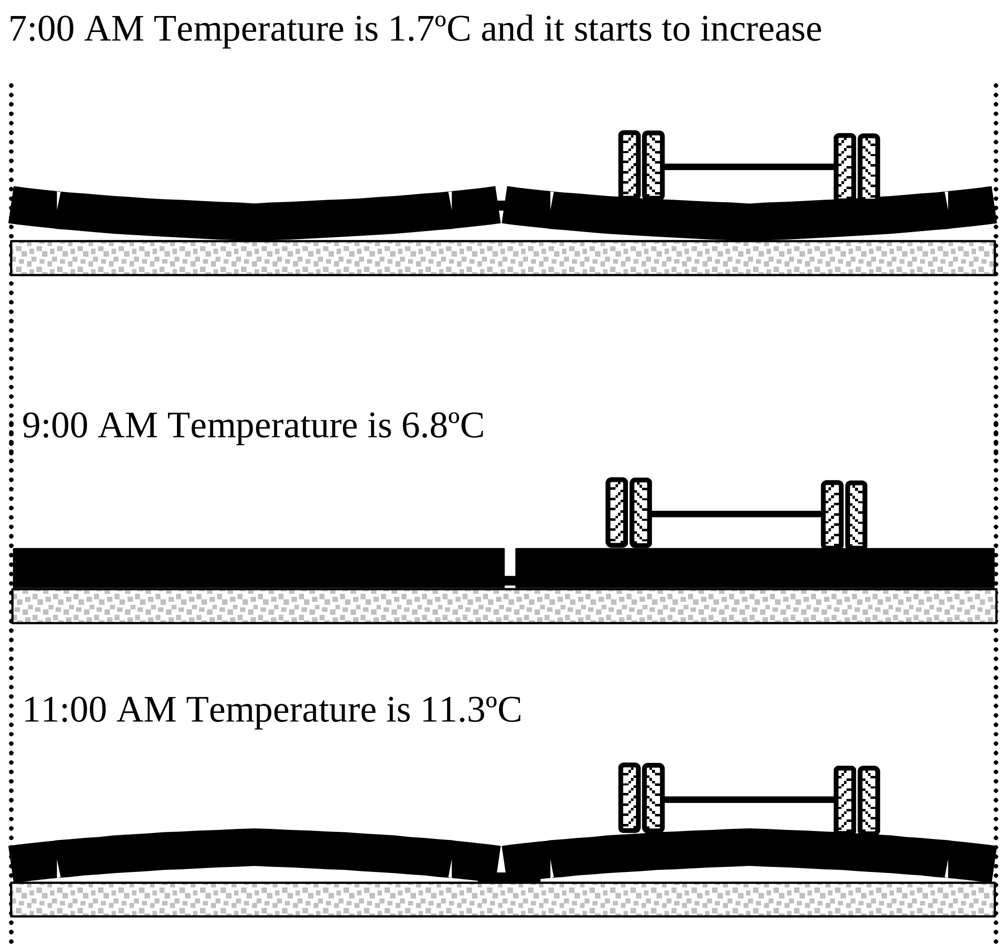


FIGURE 5 Schematic of the Expected Transverse Curling/Warping.

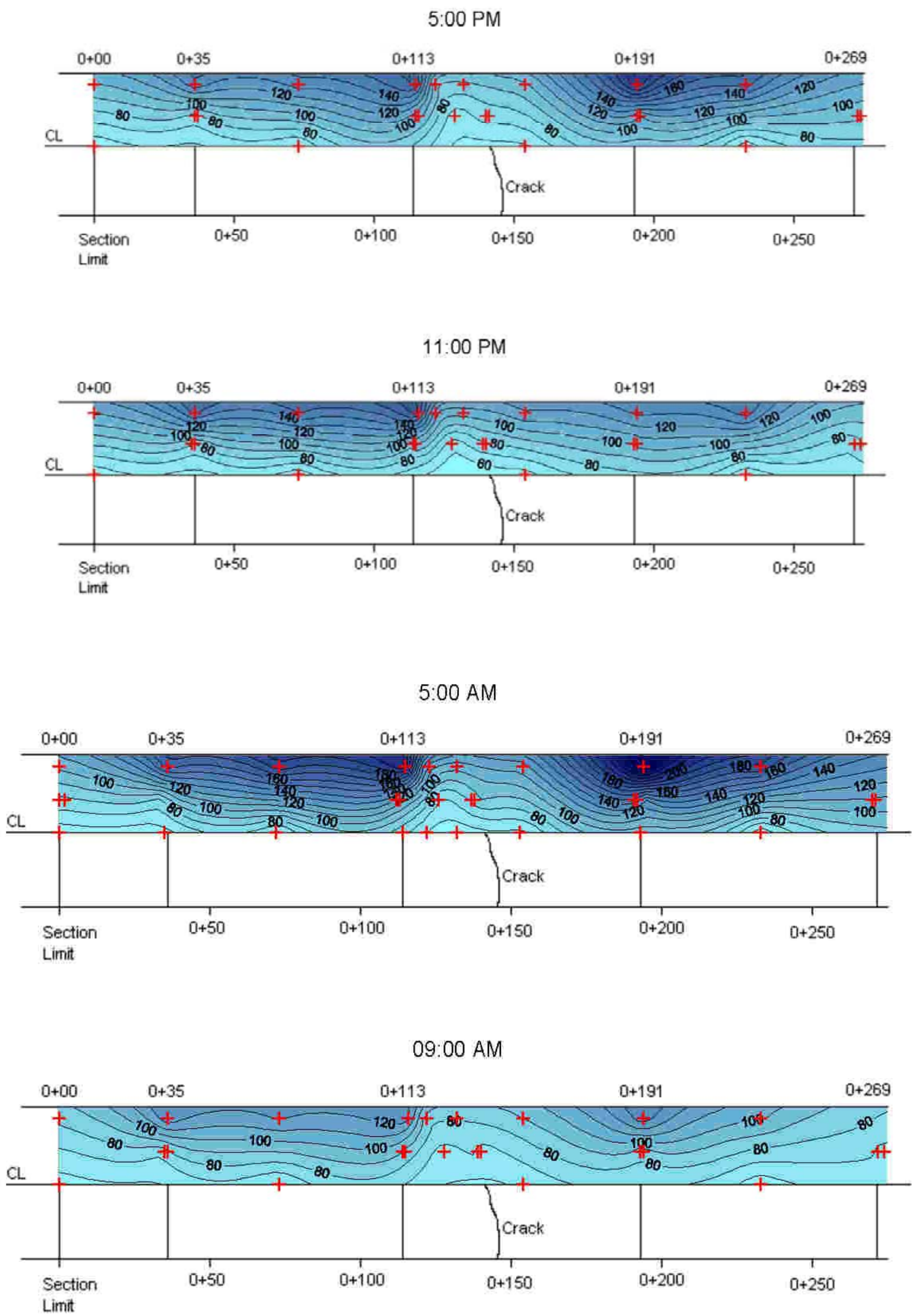


FIGURE 6 Deflection Contours of the November 2002 Cycle.

This finding indicated that comparing the wheel path or the mid-slab deflections with the edge deflection provides some information about the slab curling status. Therefore, the relationship between mid-slab/wheelpath deflections and edge deflection was further investigated.

Edge – Mid-slab Deflection Relationship

Previous studies indicated that for a fully supported slab, the edge deflection is expected to be in the range of 2.0 – 2.5 times of the mid-slab and wheel path deflections (4). However, this ratio is expected to change if slab curling occurs. The edge/mid-slab deflection ratio was calculated for the November 2002 testing cycle and presented in Figure 7. The deflection ratio ranged from 1.05 to 2.96. As can be seen, when the edge/mid-slab ratio is greater than 2.0, the mid-slab deflection is at lowest value and almost constant. This indicates that the mid-slab is fully supported. At that time the slab edge may not be fully supported (curled upward). However, since the edge deflection is not used to backcalculate E_{pcc}, it should not have any impact on the results. When the edge/mid-slab deflection ratio is less than 2.0, then the mid-slab is not fully supported and the edge of the slab is supported. In this case, the measured mid-slab deflection is higher than the fully supported deflection. Using the measured deflection in the backcalculation of E_{pcc} will result in lower values for the E_{pcc}, which is lower than the actual E_{pcc}. Therefore, either the measured deflection or the backcalculated E_{pcc} have to be corrected to account for the support condition of the mid-slab.

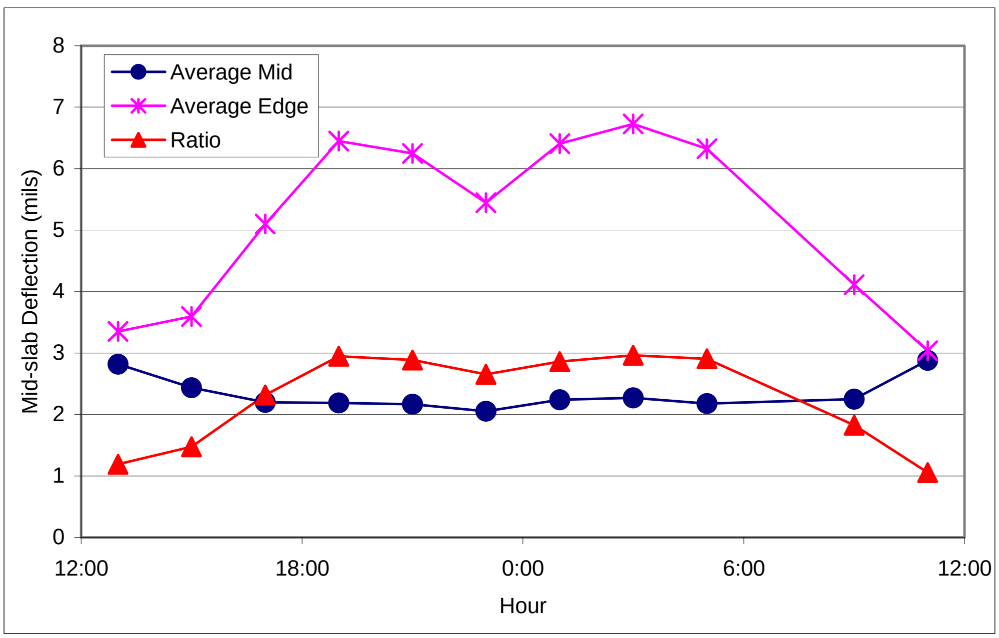


FIGURE 7 Relationship of Edge and Mid-slab Deflections (November 2002).

The edge/wheel path deflection ratio for the November 2002 testing cycle ranges from 1.05 to 2.75. It is expected that when this ratio in the range of 2.0 to 2.5, the wheel path will be fully supported. However, when the edge/wheel path deflection ratio is less than a minimum value or higher than a maximum value, the wheel path is not supported. Recalling Figure 5, the wheel path will not be supported if the slab is in either in an upward or downward curling mode. The only difference between the two cases is the ratio of the edge/wheel path deflection (higher than a upper limit, or lower than a lower limit). This finding suggests that using the edge/mid-slab deflection ratio is more desirable and gives a better indication of the slab curvature mode. However, in some cases mid-slab cannot be tested for site specific reasons, therefore the edge/wheel path deflection ratio can be used instead.

The use of the deflection ratio as an indicator for the slab curvature was further investigated. One of the reasons the slab edge deflection was used instead of the slab corner deflection in this investigation is that the slab corner deflection may provide an inaccurate picture if voids exist underneath the slab. Also, the initial (as-built) curling may have an impact. The effect of these issues at the slab edge is expected to be much less. Recalling Figures 1 and 2, it very visible that corner deflection has the highest change during the 24-hour testing cycles and is very sensitive to temperature change, which is not the case for the edge deflection. Therefore it was decided not to use corner deflections as an indicator to the slab curvature.

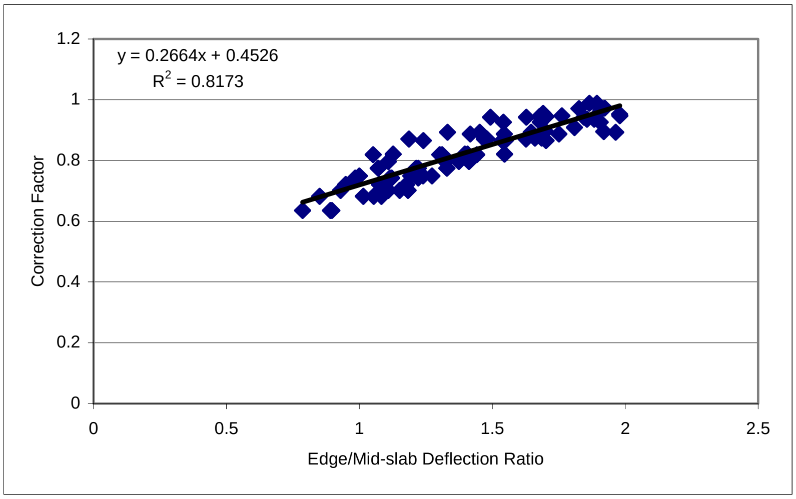
Correlation Between Edge and Mid-slab Deflections

In this approach, an assumption was made that the mid-slab will be fully supported when the measured mid-slab deflection is at its lowest value. Therefore, when the measured mid-slab deflection exceeds the minimum deflection, then the mid-slab will be in curling upward mode; and the measured mid-slab deflection needs to be corrected.

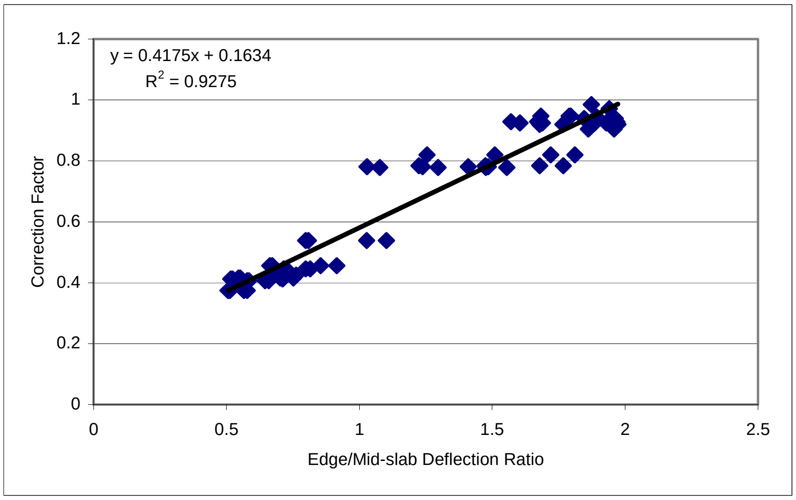
For each slab within the test section, the ratio of the measured deflection at the center of the load plate (D0) and the minimum D0 (D0(min)) measured within the 24-hour testing cycle was calculated (D0/D0(min)). This ratio represents the Correction Factor (CF) that can be applied to account for the increase in the measured D0 due to slab. Analysis was then performed to correlate the CF, which is equal to D0/D0(min) ratio and the edge/mid-slab deflection ratio. Figure 8(a) shows the results of this correlation analysis for the November 2002 testing cycle. It should be noted that the correlation analysis was performed only on the data with edge/mid-slab deflection ratio less than 2.0. This is because no deflection correction is required when this ratio is greater than 2, as the mid-slab is fully supported.

The same steps were applied on April 2003 data. Results of the correlation analysis for the April cycle are shown in Figure 8(b). As can be seen, April data shows a similar trend to that of the November data. The main difference between the November 2002 and April 2003 tests is the temperature range. During the November testing the temperature ranged from 1^{o}C to 11^{o}C, while during the April testing the temperature ranged from 12^{o}C to 22^{o}C. Therefore, the data of these testing cycles complement each other. Figure 8(c) shows the data of both testing cycles and the correlation model developed of this data. As can be seen, the developed model shows very reasonable R2. It should be noted that the model was developed for edge/mid-slab deflection ratios less than 2, because when this ratio is equal to 2.0 or higher, the mid-slab will be fully supported. Therefore, no correction is needed. To confirm that 2.0 is a good limit to use, the data of both November and April testing for all edge/mid-slab deflection ratios was plotted and shown in Figure 9.

8(a) – November 2002 Cycle



8(b) – April 2003 Cycle



8(c) – November and April Cycles

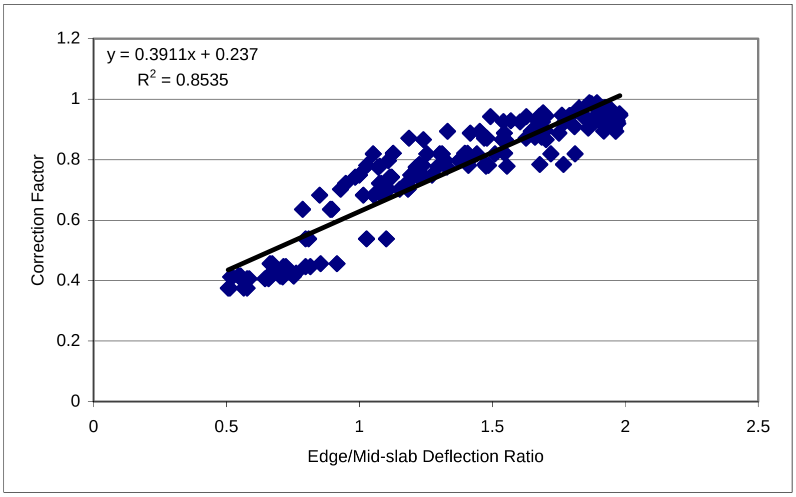


FIGURE 8 Correlation Between Edge/Mid-slab Deflection Ratio

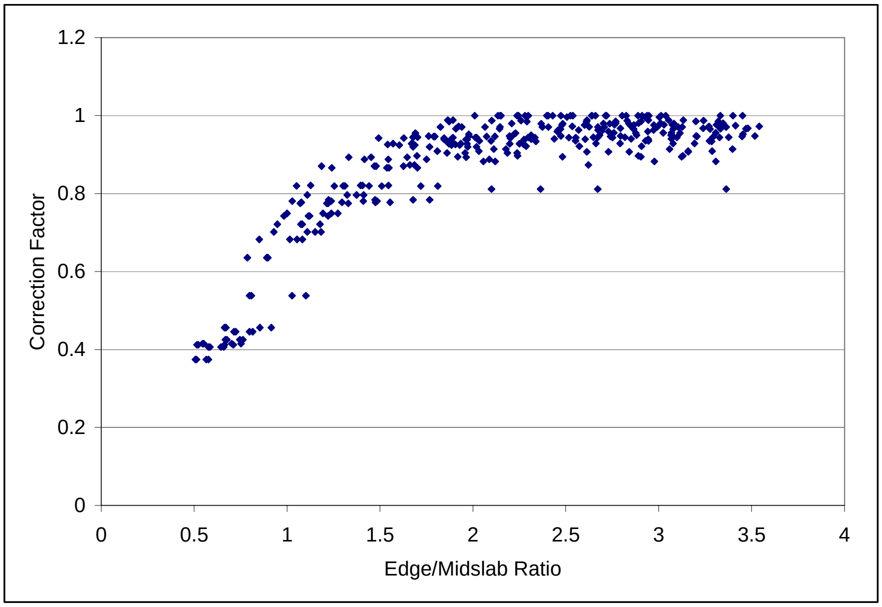


FIGURE 9 Edge/Mid-slab Deflection Ratio – All Data (November and April Cycles).

Since the effect of curling may impact the deflection measured at different offset distances and since these geophones are used in the backcalculation analysis (Geophones at 12", 24" and 36"), the same procedure was repeated on the deflections measured with these geophones. Results of the correlation analysis performed on the deflections measured at 12", 24" and 36" offset distances showed similar results of the D0 analysis.

Developed Approach

Figure 10 outlines the developed approach that can be used to account for the slab curling effect on the backcalculation analysis results. The developed approach is concerned with mid-slab deflection, which is used to backcalculate the k and E_{pcc}. This approach does not touch on other types of testing for load transfer efficiency or void detection. In the developed approach, FWD testing has to be performed at the mid-slab and edge of the desired station.

At each station, the ratio of the edge/mid-slab deflections is calculated and used as an indicator for the slab curvature (curling mode). Stations with deflection ratios equal to or greater than 2 require no correction because the mid slab at this station is fully supported, no slab curling. The mid-slab deflection at this station can be used to backcalculate E_{pcc} with no deflection correction.

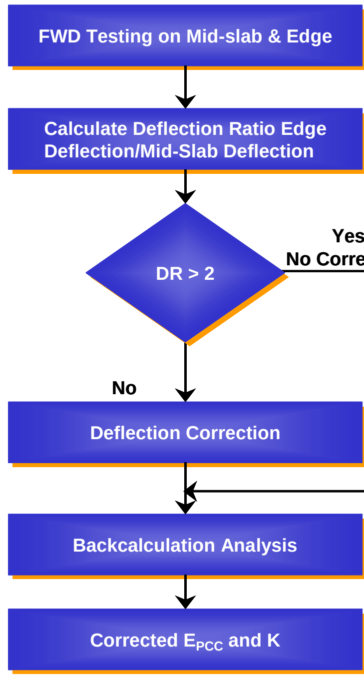


FIGURE 10 Procedure to Account for Slab Curling.

The mid-slab deflections of the stations that have deflection ratios less than 2.0 will require mid-slab deflection correction. The low deflection ratio (< 2.0) indicates that the mid-slab is not fully supported (slab in curling mode). The slab curling causes an increase in the measured mid-slab deflection (higher than normal), which will result in reduced backcalculated E_{pcc}. This reduced E_{pcc} gives artificial indication that the pavement has low structural capacity, which is not the case. Figure 11 shows a graphical presentation of the developed model that is used to account for slab curling, which is:

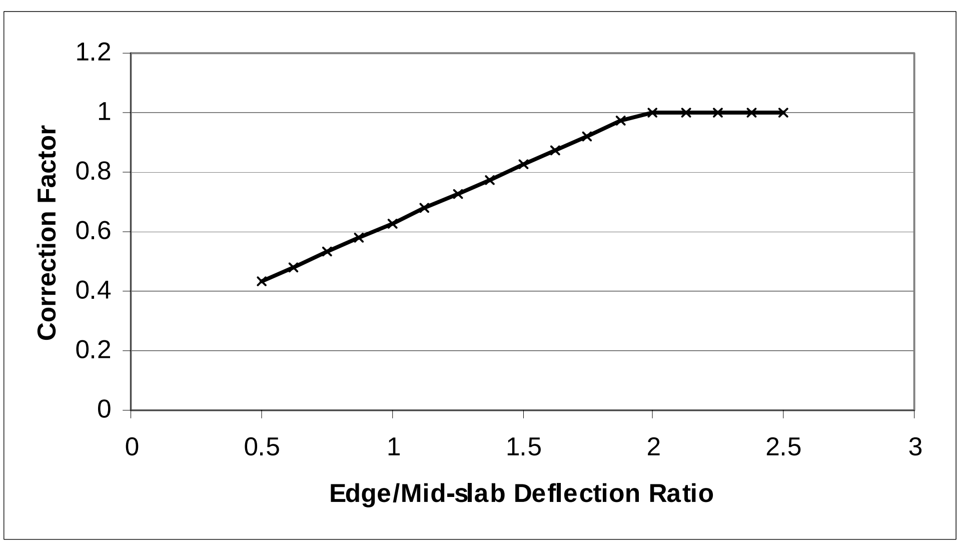


FIGURE 11 Deflection Correction Developed Model.

EDGE DEFLECTION/MID-SLAB DEFLECTION RATIO < 2
Correction Factor = a (Deflection Ratio) + b
EDGE DEFLECTION/MID-SLAB DEFLECTION RATIO >= 2
Correction Factor = 1.0
Corrected Mid-Slab Deflection = Measured Mid-Slab Deflection * Correction Factor
Where,

Correction Factor = Mid-Slab Deflection Correction Factor
Deflection Ratio = Edge Deflection/Mid-Slab Deflection Ratio
a and b = Model Parameters, which are

offset	a	b	R^2
0	0.3911	0.237	0.85
12	0.4253	0.1759	0.76
24	0.4214	0.1763	0.76
36	0.4283	0.1721	0.76

Application Example

The developed model was applied on the monthly measured D0 deflections of Sections S5 and S6. Figures 12 and 13 show a comparison between the measured mid-slab deflections and the corrected mid-slab deflections for Sections S5 and S6, respectively. It should be noted that these sections are tested on monthly basis without selecting a specific temperature or temperature gradient conditions, i.e. ambient temperature and ambient temperature gradient are randomized.

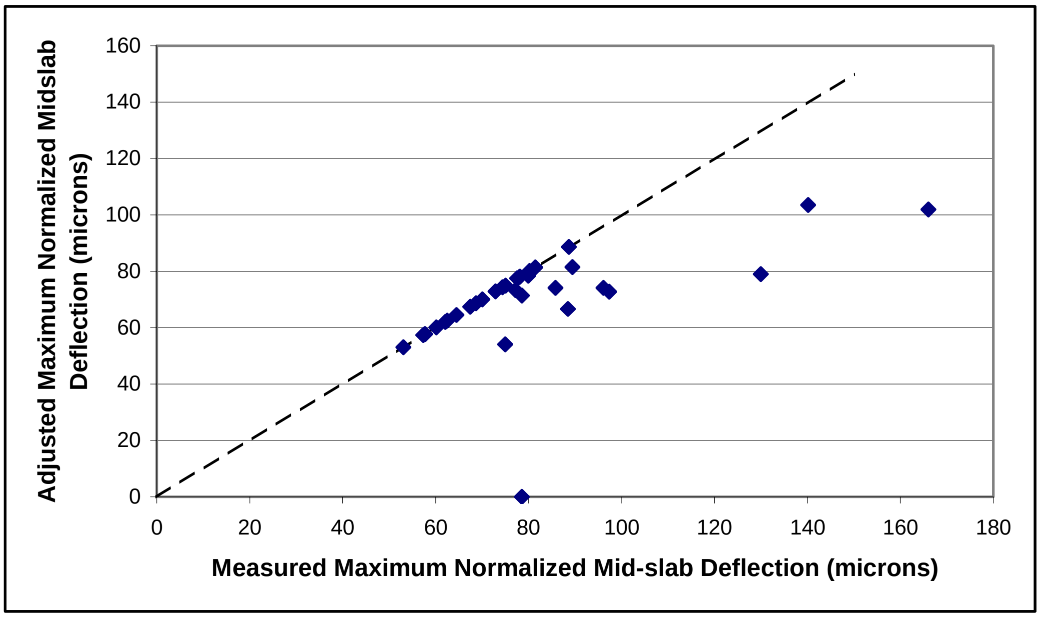


FIGURE 12 Measured and Corrected Mid-slab Deflections of Section S5.

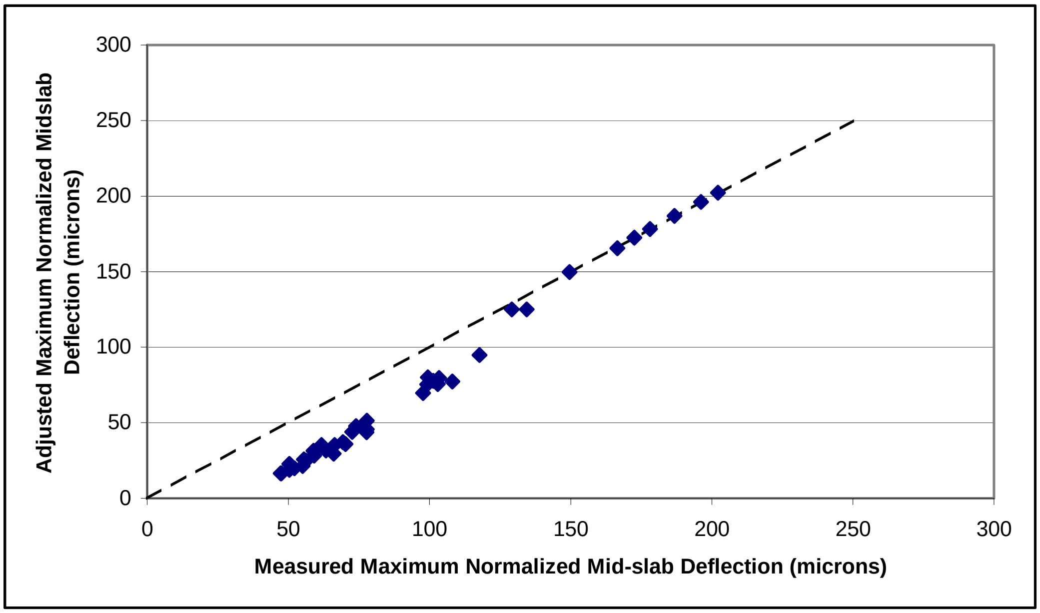


FIGURE 13 Measured and Corrected Mid-slab Deflections of Section S6.

The averages of the deflection correction factor for S5 and S6 sections are 0.9 and 0.66 respectively, while the standard deviations for S5 and S6 are 0.20 and 0.22, respectively. The mid-slab deflection basin (0”, 12”, 24” and 36”) of one of the S6 section was used to show the impact of the curling effect on the backcalculated E_{pcc}. The following is a summary of this implementation:

- Mid-slab Deflections at 0”, 12”, 24” and 36”= 3.91, 3.64, 3.48 and 3.31 microns
- Corresponding Edge Deflections = 2.69, 2.46, 2.31, 2.14
- Deflection Ratios (Edge/Mid-slab) = 0.688, 0.675, 0.664, 0.648
- Correction Factors = 0.506, 0.461, 0.456, 0.449
- Original deflection basin area = 32.913
- Corrected deflection basin area = 30.301
- Backcalculated original E_{pcc} = 1.356 million psi
- Corrected E_{pcc} = 0.905 million psi

As can be seen, the impact of curling in this example is a 33 percent reduction in the backcalculated E_{pcc}. Although this case is for a poor PCC condition, similar results may be obtained for sections with good concrete strength in terms of high backcalculated Epcc values.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A procedure was developed to account for the impact of daily temperature variation on FWD analysis results for rigid pavements. PCC slab curling that occur due to daily temperature cycles was investigated and considered in this procedure. In this procedure, correction models were developed to account for the impact of slab curling on mid-slab deflection, and hence on the backcalculated E_{pcc} and k. The procedure was developed as a part of a large-scale research study sponsored by NJDOT to study the seasonal variation in pavement properties and its impact on pavement response and performance. In this study several pavement test sections are fully instrumented with temperature, moisture, frost depth and ground water probes. FWD and SPA testing are performed on these sites on monthly basis. In addition, two, 24-hour testing cycles were performed on one flexible pavement and one rigid pavement test sections. In these cycles, FWD testing was repeated every two hours for 24-hour period.

Results of the 24-hour testing cycles showed a significant increase in the mid-slab deflection within 2 hours during the testing cycles. Also, it was found that corner deflections are the most sensitive deflections for temperature change, while the mid-slab deflections are the least sensitive deflections to temperature change. Results of the backcalculation analysis performed on the 24-hour testing cycles indicated very significant change in the backcalculated E_{pcc} and k during the testing cycles. On the other hand, the change in LTE was limited.

An effort was made to develop a procedure that can first identify if the slab in curling mode, and account for the impact of slab curvature on the backcalculation analysis results. The ratio of the edge and mid-slab deflections provided good indication about slab curling. Correction models were developed for the deflections measured at different offset distances (Geophones at 12", 24" and 36") to account for the slab curling effect.

Implementation example showed that the averages of the deflection correction factor for S5 and S6 are 0.9 and 0.66 respectively, while the standard deviations for S5 and S6 are 0.2 and 0.22 respectively. The developed procedure is currently in the pilot implementation stage in New Jersey.

Since slab curling was found to have a significant impact on the measured wheel path and mid-slab deflections, it is recommended to implement the developed procedure to account for such impact.

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LIST OF FIGURES