ENIRONMENTAL EFFECTS OF EARLY AGE AND LONG TERM RESPONSE OF PCC PAVEMENT

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ABSTRACT

Early age deformation of PCC pavements caused by built-in gradients and warping can result in a permanent loss of support, which significantly influences its long term performance. This study quantifies the environmental influences on early age response of PCC pavement. Two adjacent slabs located in the driving lane of west bound I-490 in Rochester, New York, were instrumented to monitor concrete temperature and strain, and pavement deformation. Immediately after slab placement, readings from temperature, strain and displacement sensors were taken continuously for 48 hours. Additionally, in the sixth week after placement a twenty-four hour cycle was investigated. Since the pavement was placed during hot weather conditions, the resulting negative built-in gradient and high shrinkage caused a significant upward deformation after 48 hours. In the sixth week, warping caused the pavement to experience a permanent loss of support independent of the temperature gradients which were observed. The phenomenon of permanent loss of support was also investigated by means of FWD Testing. Test results of the FWD were very consistent with the other data describing the pavement deformation. Vibrating wire strain measurements were used to investigate the increase of tensile stresses in the top strata due to upward curling. Significant tensile stresses solely due to environmental factors were determined.

Portland Cement Concrete (PCC) used for highway surface construction experiences significant forces due to environmental factors. Environmental conditions such as air temperature and humidity act like scaling factors for the stresses caused by traffic. These factors affect the pavement from the time curing starts and continue to influence it for the duration of its life. Early deformation caused by built-in gradients and warping is thought to result in a permanent loss of support under the pavement, which influences its long term condition. The performance of PCC pavement can be affected by ambient temperature and humidity during curing, heat of hydration, and shrinkage.

This study examined the effects of environmental cycling on early age response of PCC pavement, and on initial and subsequent slab shaping. These factors include ambient temperature during curing and the resulting built-in gradient and shrinkage.

During the week of June 10, 2002, two adjacent slabs located in the driving lane of west bound I-490 in Rochester, New York, were instrumented to measure environmental strain and vertical deflection during pavement curing. These slabs were part of the reconstruction of I-490 in Rochester. The pavement consisted of jointed 250mm thick concrete with 5m joint spacing and a 4.26 m wide driving lane. The concrete was placed on top of a 100 mm thick permeable concrete treated base.

INSTRUMENTATION, LAYOUT AND MATERIAL PROPERTIES

An award winning instrumentation technique was used to install sensors in the pavement during the paving process. This technique, developed at Ohio University and used on several highway instrumentation projects, involves the placement of sensors in the concrete during the paving process with minimal disruption to the contractor and without damaging the pavement.

Two slabs, Slab 1 and Slab 2 were instrumented with strain and deflection sensors to measure early environmental response of the concrete, as shown in Figure 1. Four thermocouples were installed at the center and edge of Slab 1 to monitor temperatures in the slab at 13, 79, 152, and 222 millimeters from slab bottom.

Four deep referenced Linear Variable Differential Transformers (LVDTs) were used to measure the environmental deflection response of Slab1. This installation included: the drilling of three meter deep holes, the grouting of steel reference rods in the bottom of the holes to provide references for the LVDTs, the positioning of specially fabricated LVDT holders at the proper elevation in the pavement slab, and the placement of LVDTs in the holders prior to placement of the concrete. Monitoring of the LVDTs was initiated just prior to placement of the concrete.

One set of two Geokon VCE-4200 vibrating wire strain gauges was placed at the center of the slab and second set was placed at the edge of the slab to ascertain the distribution of environmental strain throughout the slab area. At each strain gauge location, one gauge was installed 210 mm from the bottom, the other at approximately 35 mm from the bottom.

Dipstick® 2000 surveys were collected to determine the shape of the slabs during curing, before and after joint saw cutting, and subsequently to capture the effects of different temperature gradients. The inside perimeter and diagonal of each slab were recorded as shown in Figure 2. To ensure accuracy, each Dipstick survey line was repeated twice.

NYDOT Class C mix, Table 1, was used in this pavement, with desired 28 day strength of 31.5 MPa. Table 2 presents the seven day results of the Modulus of Rupture. The coefficient of thermal expansion of the concrete was 12x10^-6 per degree Celsius and the Elastic Modulus was 29,000 MPa.
MONITORING INITIAL CURING IN THE FIRST 48 HOURS

LVDT, strain gauge and thermocouple readings were recorded continuously for the first 48 hours after slab placement to investigate early age pavement behavior. Data collection began at 9:00 am and the test sections were placed at approximately 10:00 am. All data will be referenced to 9:00 am.

Temperature Data

The pavement was placed during hot weather conditions in June. The air temperature reached a maximum of 35°C approximately five hours after slab placement. Air temperature and temperature gradients in the center of the slab during the first 48 hours after concrete placement are shown in Figure 3.

Due to the combined effects of heat of hydration and solar radiation, the highest temperatures were recorded in the top strata of the slabs during the day of placement. The maximum temperature difference measured between the top and bottom thermocouples was nearly 6°C. Negative temperature gradients developed during the first night and during the second day when the daytime air temperature was below 20°C and hydration continued to generate heat in the lower portion of the slabs. The greatest negative gradient was recorded after about 24 hours when a thunderstorm passed the area.

Due to the enormous build up of heat in the first hours, the pavement slabs experienced high temperature gradients while cooling down. This process resulted in high thermal stresses and an almost immediate cracking of the transverse joints after cutting.

Built-in Gradient

Initial slab curvature is directly related to temperature distributions through the slab depth during concrete hardening. Temperature gradients due to the combined effects of radiation and heat of hydration develop during the initial curing of the pavement. These early gradients cause no significant thermal stresses since the pavement is an infinite slab in the longitudinal direction and stress relaxation occurs while the concrete is still plastic. The concrete eventually sets with the so-called zero-stress temperature gradient or built-in gradient with the slab in a flat position [1], [2].

When exposed to hot ambient air temperature and solar radiation during initial curing, the slabs develop a negative built-in gradient. A negative built-in gradient occurs because the hardened slabs have an effective built-in gradient of the opposite sign of the measured gradient the slabs were exposed while the concrete was still plastic. As a result, the slab will remain flat only when the positive gradient is present. When this gradient dissipates, the slab reacts as if it is under a negative gradient and the slab curls upward. Thus, pavement placed during hot weather produces built-in curling, which creates high tensile stresses on top and is likely to result in cracks due to cantilever action under traffic loads.

At the center of Slab 1, the temperature distribution during the initial curing indicates a positive built-in gradient. Figure 4 shows the temperature gradient at the center of the slab for a period of 4.5 hours between the time of final setting and the cutting of joints which was 9.0 hours test time.

Final setting refers to the time when concrete turns from a liquid to a solid stage. In accordance with reference [3], the final setting time after mixing concrete can be determined from the following equation:

\[
\text{Final setting time (min)} = 90 + 1.2 \times \text{initial setting time (min)}
\]  

(1)

The initial setting time occurs when the concrete temperature starts to rise. The heat of hydration caused the temperature at the slab center to begin to rise approximately 2.5 hours test time. From Equation 1, the final set of the concrete was determined to be 5.5 hours after mixing or 4.5 hours test time.

After cutting of the joints, slab temperatures approached a negative gradient. Thus, the resulting deflection due to the positive built-in gradient was upward curling. However, the deformation process is more complex since shrinkage occurs simultaneously and thus, curling and warping act at the same time. The contribution of warping to permanent pavement deformation will be discussed below.

Pavement Deformation Data

To define pavement deformation in the first 48 hours, Dipstick® surveys were taken three times after saw-cutting. The first survey was taken immediately after the joints were cut and all data references this survey, i.e. all Dipstick® plots show deformation relative to this point in time. LVDT readings were taken in addition to the Dipstick® surveys to give more precise descriptions of pavement deformations over time.

Dipstick® surveys

Dipstick® surveys were taken on different slabs. Since the data are very consistent, however, plots of only one slab are presented in this paper. The LVDT data, which are discussed below, were used to calibrate the Dipstick® data for Slab 1. Deformations in the Dipstick® plots at the LVDT locations (Figure 1) coincide with the actual LVDT readings at this time. The difference in Dipstick® readings after 30 hours and 48 hours test time was negligible, since the negative temperature gradient after
Warping and Permanent Loss of Support

Warping is an ongoing process which causes permanent pavement deformation throughout, at least, the first 8 week of curing [4]. In the sixth week after pavement placement, warping had a significantly greater influence on the loss of support than did the built-in gradient, since high concrete temperatures and solar radiation lead to a very high shrinkage rate on the pavement surface.

Warping, when the slab bottom is wetter than the top, caused the pavement to experience a permanent loss of support independent of the observed temperature gradients. In spite of a relatively high positive gradient of almost 6°C Celsius, that is the slab tends to curl upward, the slab corners still showed a significant amount of deflection, as it can be seen in Figures 9 and 10. LVDT 1, in the slab middle along the shoulder, was the only LVDT which indicated full slab-base contact at the time of the greatest positive gradient.

FWD Testing

The phenomenon of permanent loss of support was also investigated by means of Falling Weight Deflectometer (FWD) Testing. On three slabs, with both extreme gradients present, FWD tests were conducted in alignment to a grid shown in Figure 11.

Only results of one slab are presented since the data were very consistent. For each drop location, maximum deflections under an approximate 71 kN load are plotted for the negative gradient in Figure 12 and for the positive gradient in Figure 13.

Test results of the FWD were very consistent with the other data describing the pavement deformation. Based on whether the pavement was in full contact with the base or acting like a cantilever tremendous differences in deflection occurred. Deflections in the center of the slab do not change significantly with temperature, whereas the edges experienced a permanent loss of support along the transverse joints with the maximum positive gradient.

Pavement Stresses due to Curling

Vibrating wire strain gauge measurements were used to investigate pavement stresses due to curling. Although it is not feasible to determine the amount of absolute stresses, the increase of tensile stresses in the top strata of the pavement due to upward curling was calculated based on strain readings.
Actual concrete strain in a 24-hour cycle is primarily determined by changes in temperature. This strain follows the pattern of ideal thermal strain calculated by temperature difference times the coefficient of thermal expansion of concrete. However, ideal thermal strain cannot be observed since stresses due to dead load of the slab are present. In Figure 14, the ideal thermal strain for the 24-hour cycle is plotted versus actual strain readings for the vibrating wire location in the slab center.

The plot is typical for environmental pavement response. Characteristically, differences between maximum and minimum actual strain are smaller for the top strata than the ideal thermal strain suggests and larger for the bottom strata. This is caused by increasing tensile stresses on top of the slab when it cools down and the corresponding negative gradients.

Focusing on the points in time with the extreme gradients, strain due to curling can be determined with:

$$\varepsilon_{\text{curling}} = \Delta \varepsilon_{\text{ideal thermal}} - \Delta \varepsilon_{\text{actual}}$$

where

- $\varepsilon_{\text{curling}}$ = strain due to curling
- $\Delta \varepsilon_{\text{ideal thermal}}$ = difference in ideal thermal strain based on the temperatures with both extreme gradients
- $\Delta \varepsilon_{\text{actual}}$ = difference in actual strain readings with both extreme gradients

Longitudinal tensile stresses due to curling are 0.8 MPa in the center and 1.0 MPa close to the edge, applying equation (2) with vibrating wire strain gauge readings and materials properties measured in the laboratory. This is a significant amount of stress for pure environmental response, especially since the actual maximum tensile stresses in the pavement will be even larger. The gauges did not read the principle strain, were set 40 mm below the slab surface and at only at two locations on the slab. Furthermore, even with the greatest positive gradient, tensile stresses were already present in the top pavement strata due to loss of support.

CONCLUSIONS

PCC Pavements placed during hot weather can develop negative built-in gradients which lead to significant upward deflections as early as the second day after placement. The influence of built-in curling must not be neglected in modeling the initial curing period. Pavements with negative built-in gradients experience high tensile stresses on top and are likely to develop top-down cracks under traffic loads.

However, if PCC pavements are exposed to high air temperatures and solar radiation during curing, warping can have a significantly greater influence on the loss of support than the built-in gradient. Warping can cause the pavement to experience a permanent loss of support, which can not be reversed even by extreme positive temperature gradients.

When a concrete shoulder is not present when the driving lane is placed, the outer edge can experience high permanent deformations. The result is a permanent loss of support under the slab corners along the shoulder side of the pavement.

FWD tests confirm other data with regard to pavement deformation. Deflections show significant differences based on whether the pavement is in full contact with the base or acting like a cantilever. The permanent loss of support can be determined with FWD.


### TABLE 1  
**Mix Design NYDOT Class C**

<table>
<thead>
<tr>
<th>Material</th>
<th>Kilogramm per Cubic Meter</th>
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<tbody>
<tr>
<td>Water</td>
<td>158</td>
</tr>
<tr>
<td>Cement</td>
<td>287</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>72</td>
</tr>
<tr>
<td>Fine Aggregates</td>
<td>634</td>
</tr>
<tr>
<td>Coarse Aggregates (#1 Stone; 40% Split)</td>
<td>454</td>
</tr>
<tr>
<td>Coarse Aggregates (#2 Stone)</td>
<td>682</td>
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<tr>
<td>Water – Cement Ratio</td>
<td>0.44</td>
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### TABLE 2  
**Modulus of Rupture Test Results**

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<thead>
<tr>
<th>Age (Days)</th>
<th>Modulus of Rupture (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.6</td>
</tr>
<tr>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>3.7</td>
</tr>
<tr>
<td>5</td>
<td>4.3</td>
</tr>
<tr>
<td>7</td>
<td>4.5</td>
</tr>
</tbody>
</table>

### TABLE 3  
**Warping with Time at Varying Slab Locations**

<table>
<thead>
<tr>
<th>LVDT 1</th>
<th>LVDT 2</th>
<th>LVDT 3</th>
<th>LVDT 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading on 2nd Day (mm)</td>
<td>Reading on 37th Day (mm)</td>
<td>Warping Difference (mm)</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>1.1</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>3.2</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>1.3</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>1.6</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 1 Instrumentation Layout

FIGURE 2 Dipstick® survey
FIGURE 3  Temperature Development in the Slab Center within the - Initial 48 Hours

FIGURE 4  Temperature Distribution in the Slab Center after Final Set – Initial 48 Hours
FIGURE 5  Shape of Slab after 48 Hours Test Time

FIGURE 6  LVDT - Initial 48 Hours
FIGURE 7  Temperatures in Slab Center and Air Temperature – Six Weeks After

FIGURE 8  Gradient in the slab center versus LVDT Readings – Six Weeks After
FIGURE 9 Dipstick® Plot for the Maximum Negative Gradient – Six Weeks After

FIGURE 10 Dipstick® Plot for the Maximum Positive Gradient – Six Weeks After
FIGURE 11 Grid for FWD Tests

FIGURE 12 Deflections under FWD Testing at the Greatest Negative Gradient – Six Weeks After
FIGURE 13 Deflections under FWD Testing at the Greatest Positive Gradient – Six Weeks After

FIGURE 14 Ideal Thermal Strain versus Actual Strain Readings – Six Weeks After
REFERENCES