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EARLY-AGE RESPONSE OF CONCRETE PAVEMENTS TO TEMPERATURE AND MOISTURE VARIATIONS

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Abstract. In this paper, the early-age response of a Jointed Plain Concrete Pavement (JPCP) to temperature and moisture variations at the time of paving and immediately following construction is discussed. A newly constructed JPCP on US-30 near Marshalltown, Iowa, USA was instrumented and monitored during the critical time immediately following construction to identify its early-age behavior with respect to pavement deformation due to temperature and moisture variations. The instrumentation consisted of Linear Variable Differential Transducers (LVDTs) at the slab corner, center, and edges, and thermocouples and humidity sensors installed within the slab depth. The slab deformation associated with temperature and moisture variations were quantified using field-measured vertical displacements and pavement surface profiles. The positive temperature gradients during setting times and the negative moisture difference after setting times caused permanent upward curling and warping in the instrumented pavement. The relative corner deflection of the slab to center or mid-edge calculated using the slab profile and LVDT measurements show similar trends.

Keywords: concrete, pavements, curling, warping, temperature and moisture variation.

1. Introduction

The temperature and moisture variations across the depth of the Portland Cement Concrete (PCC) pavements due to changes in the climate result in a unique deflection behavior which has been recognized as curling and warping of the pavements since mid 1920 (Westergaard 1927). According to 2004 *National Cooperative Highway Research Program (NCHRP) "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures"*, Project 1-37A in the USA, in general, temperature differences across the depth of the concrete pavement result in curling while moisture differences result in warping behavior. 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., under no external forces that cause slab distortion (Yu *et al*. 2004).

Curling and warping of PCC slab influences the degree of support by subgrade and the stiffness along the joint (Armaghani *et al*. 1986, 1987). The weight of the slab tends to hinder the curling and warping deformation from taking place and as a result restraint stresses are induced within the concrete slab (Huang 1993).

The early age behavior of PCC is significantly influenced by temperature, moisture, and creep of concrete (Rao *et al*. 2001). Based on profilograph records of concrete pavements in California, Hveem (1951) concluded that slab curling was due to the combined effect of temperature and moisture, both of which change non-uniformly through the depth of the slab. Many significant research efforts in the past have tried to address the combined effects of temperature, moisture, and creep on the early-aged slab behavior (Jeong, Zollinger 2005). A positive temperature difference between the top and the bottom surfaces

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of the concrete slab in daytime causes the slab corners to curl downwards, while a negative temperature difference during night time results in the upward curling of PCC. The moisture difference through the slab depth because of weather condition results in non-uniform concrete shrinkage and non-uniform volume changing through depth (Rao *et al.* 2001). However, curling and warping behavior of early aged concrete is affected by not only temperature and moisture differences due to weather conditions but also early age curing conditions and temperature conditions during pavement construction (Rao *et al.* 2001; Rao, Roesler 2005; Yu *et al.* 1998)

A significantly irreversible drying shrinkage of concrete near the top of the slab and a positive temperature gradient at the time of concrete setting can cause permanent upward curling and warping at zero temperature gradient (Yu *et al.* 2004). This permanent curling and warping (built-in curling and warping) is partially recovered by the creep of the slab after hardening of the concrete over time (Rao *et al.* 2001; Rao, Roesler 2005). Once the pavement attains permanent curling and warping after setting, the upward curling of the slab for the first few nights after the placement of concrete is the critical condition for early age cracking because the tensile stresses at the top due to upward curling and slab weight are greater than incompletely developed concrete strength (Lim, Tayabji 2005).

Limited experimental research studies (Armaghani *et al.* 1987; Jeong, Zollinger 2005; Lim *et al.* 2009; Rao *et al.* 2001; Wells *et al.* 2006; Yu *et al.* 1998) have been undertaken to better understand the actual behavior of the concrete under pure environmental loading. 2004 *National Cooperative Highway Research Program (NCHRP) "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures"*, Project 1-37A note, that in addition, the new Mechanistic-Empirical Pavement Design Guide (MEPDG) for the design of new and rehabilitated pavement structures in the USA require quantifying the permanent curling and warping in terms of temperature difference.

In spite of many research efforts, the early-age curling and warping behavior of PCC pavements under environmental conditions has not been fully understood. The primary objective of this study was to measure and analyze the early-age Jointed Plain Concrete Pavement (JPCP) behavior in terms of changes in pavement deflections to temperature and moisture variations. To achieve this objective, a newly constructed JPCP slab on US-30 near Marshalltown, Iowa was instrumented to monitor the pavement response to temperature and moisture variations during the first seven days after the construction in the summer of 2005. A series of laboratory tests were undertaken to characterize the properties of paving material during the controlled field evaluation. The instrumentation installed within the pavement is described. The procedure and the results of data analysis using the collected data from the instrumented pavement are discussed in this paper highlighting the important findings regarding the early-age curling and warping behavior of JPCP slabs.

2. Instrumentation and data collection

The test JCPC pavement was constructed on an open-graded granular base. The transverse joint spacing was approximately 6 m (20 ft). The passing lane was approx 3.7 m (12 ft) in width, and the travel lane was approx 4.3 m (14 ft) in width. A Hot Mix Asphalt (HMA) shoulder was added approx 2 months after initial construction.

Tie-bars of 914 mm (36 in) length and 12.7 mm (0.5 in) diameter were inserted approx every 76 mm (30 in) across the longitudinal joints. Dowel bars of 457 mm (18 in) length and 38 mm (1.5 in) diameter were inserted approximately every 305 mm (12 in) across the transverse joints.

Two test sections, one corresponding to late morning (11:00 AM CST) construction conditions and the other representative of afternoon (3:30 PM CST) construction, were selected for surface profile measurements. Temperature sensors, relative humidity sensors, and Linear Variable Differential Transducers (LVDTs) were placed in each section to observe the environmental effects on the slab behavior during early age (7 day after construction) without traffic loading. Iowa State University's (ISU's) PCC mobile laboratory parked near the test section monitored the weather conditions such as ambient temperature, ambient relative humidity, wind direction and rainfall on special days. During the field evaluation periods, sky was clear and sunny.

To obtain the fundamental physical properties of the paving material, a series of laboratory tests at various ages were conducted in ISU's PCC mobile laboratory and ISU's PCC laboratory using in-situ samples obtained from the paving site. The split tensile test (ASTM C 496), the compressive strength test (ASTM C 39), and the elastic modulus test (ASTM C 469) was performed on PCC samples obtained during construction. The results of laboratory tests are available in Kim (2006). In addition, the coefficient of thermal expansion (CTE, AASHTO TP 60) was measured to be 9.63×10^{-6} /°C (5.35×10^{-6} /°F).

2.1. Pavement temperature and relative humidity instrumentation

Temperature and humidity sensors installed within the test sections recorded the slab temperature and moisture data at five- minute intervals throughout the field evaluation periods. Temperature instrumentation consisted of Thermochron I-buttons attached to a stake at different depths from pavement surface (64 mm, 89 mm, 114 mm, 165 mm, 190 mm, 266 mm, 419 mm) and placed at 0.9 m (3 ft) from the pavement edge before the paving. Humidity instrumentation consisted of Hygrochron I-Buttons inserted into small Poly Vinyl Chloride (PVC) pipes which were placed side by side at different depths from pavement surface (38.1 mm, 88.9 mm, 127 mm, 165.1 mm).

2.2. Measurement of vertical slab movements using LVDT

Two slabs (slabs 19 and 20) which were paved in the afternoon were selected as representative slabs to study the pavement vertical movements entirely due to environmental loads. As shown in Fig. 1, LVDTs were installed in special locations on each slab to capture the vertical movements of the slab. In the test slab19, nine LVDTs were installed at corners, the mid-slab edges and the center of the slab. In the test slab20, seven LVDTs were installed at the corners, the mid-slab edges near longitudinal joints and transverse joints. All the sensors were placed only after the concrete hardened (1 day after paving). LVDTs were held by a bracket fastened to the steel rod inserted in subgrade and placed on a smooth glass on the PCC pavement. The LVDTs were connected to data loggers, which collected data at 10 min interval throughout the field evaluation periods.

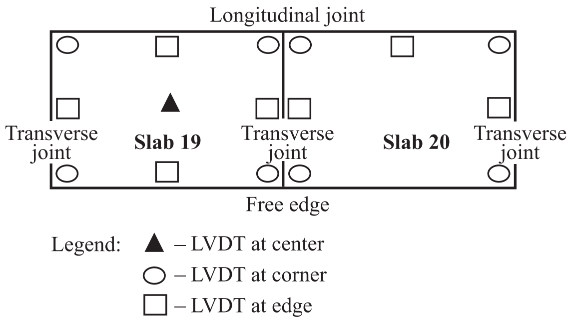

Fig. 1. LVDT instrumentation layout

2.3. Pavement surface profile measurement

Rollingprofiler by an International Cybernetics Corporation was used for surface profile measurements at different times (morning and the afternoon) in both test sections. Rollingprofiler, a kind of inclinometer profiler, can measure true unfiltered elevation profile of surface along the line being profiled (ICC 2006) Many researchers have used the inclinometer profiler measurements to quantify slab curvature (Rao *et al.* 2001; Vandenbossche 2003). Rollingprofiler measurements in this study followed transverse and diagonal traces to capture the slab curvature. Measurements were made on four individual slabs in both test sections at different times. Each profiling segment was measured independently.

3. Analysis of temperature and moisture

The temperature and moisture variations within the PCC pavement during early-age (7 days after construction) could be obtained from the installed temperature and moisture sensors. In addition, average pavement temperatures, differences in temperature and moisture between the top and bottom of the pavement, and temperature distributions with depth could be obtained from the measured temperature data.

Average pavement temperatures were calculated from temperature readings of six temperature I-button sensors (Sensor 1, 2, 3, 4, 5 and 6). Temperature differences were calculated by subtracting the temperature sensor reading at 266.7 mm below the slab surface (Sensor 1) from the sensor reading at 63.5 mm below the slab surface (Sensor 6). Note that the closest temperature sensor to the top of the pavement surface was located at 63.5 mm below the slab surface. Moisture differences were computed by subtracting the moisture sensor reading at 165.1 mm below the slab surface (Sensor 1) from the sensor reading at 38.1 mm below the slab surface (Sensor 4). Air temperature, average pavement temperature and subgrade temperature variations during the initial day (day 0 after paving) and during the early aged days (6 and 7 days after paving) are compared in Figs 2 and 3. Weather conditions were clear and sunny during both days. In both Figs 2 and 3, average pavement temperatures are higher than ambient temperature.

From Fig. 2, it can be observed that the average pavement temperature within 8 h of paving increases and reaches a max value, while air temperature decreases. The same trend is observed during the first 8 h of paving for both the test sections. After 8 h of paving, the pavement temperature follows a pattern that is similar to that of air temperature as reported by previous research study (Armaghani *et al.* 1987). This increase in pavement temperature within the first 8 h of paving may be due to the heat of concrete hydration at the time of setting. Note that after 8 h of paving, the max and min pavement temperatures occurred normally 1 to 2 h after air temperature reached their maxima and minima. Armaghani *et al.* (1987) reported that this trend was observed in the majority of the samples that were randomly selected from the collected temperature data obtained over a period of 3 years in Florida. Both from Figs 2 and 3, the subgrade temperature variation is not high and usually follows the pattern of pavement temperature.

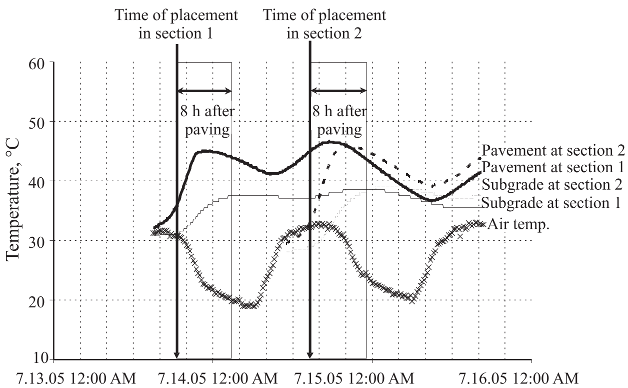

Fig. 2. Temperature variation with time during paving

In-depth temperature distributions within 12 h and 7 days of paving in test section 1 are plotted in Figs 4 and 5, respectively. It can be observed from Fig. 4 that within 12 h of paving, temperature distributions shifted towards the right. This means that the pavement temperatures at night time were higher than those of day time without increase in air temperature. Also the mitigation of temperature due to heat of hydration of concrete occurred through the thickness. From Fig. 5, the max positive temperature difference decreased with depth whereas the max negative temperature difference increased with depth with the air temperatures changing.

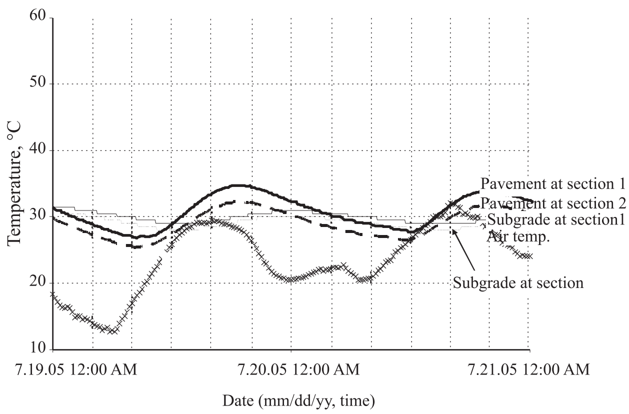

Fig. 3. Temperature variation with time during early aged days (day 6 and day 7)

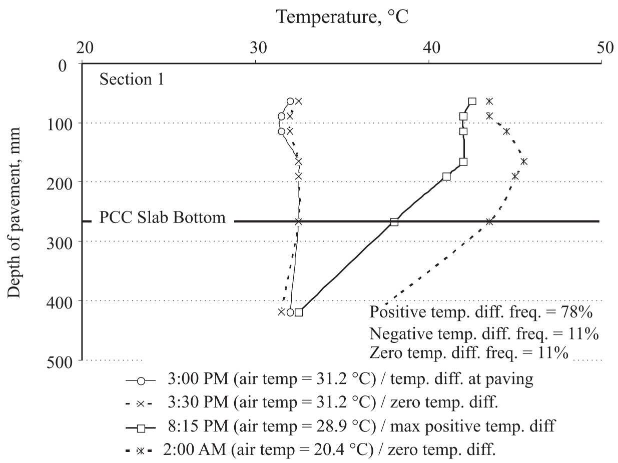

Fig. 4. Pavement temperature distributions with depth in 12 h after paving

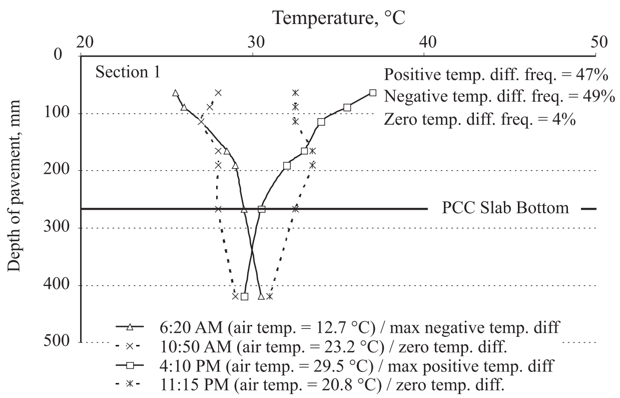

Fig. 5. Pavement temperature distribution with depth in 7 days after paving

Within 12 h of paving, the concrete hardened at the positive temperature difference condition (78%) rather than the negative temperature difference condition (11%). The laboratory test results showed that within 12 h, the PCC achieved 50% of the 28-day compressive strength. Thus, if 12 h after paving is assumed to be sufficient for the

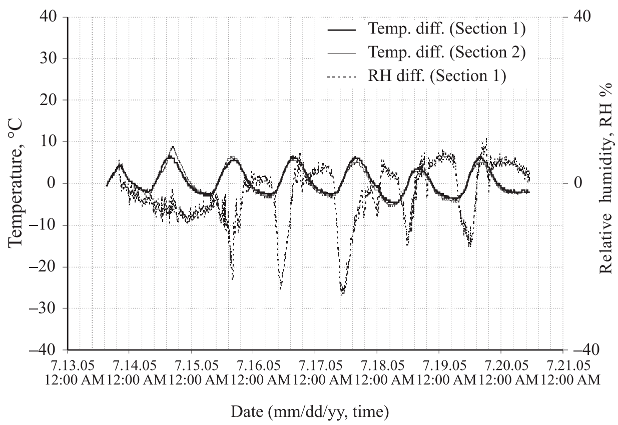

Fig. 6. Pavement temperature and moisture difference between the top and the bottom of slab with time

PCC to acquire a certain degree of hardening, a flat slab condition in this test section could be associated with a positive temperature gradient rather than a zero temperature gradient.

The variations in PCC slab curvature were influenced not only by temperature difference but also moisture difference between the top and the bottom of the slab surface. The variations in temperature and moisture differences with time are plotted in Fig. 6. 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. 6 show the reverse trend. Especially between day 0 and day 2 after paving, moisture differences are negative for most part, i.e., higher moisture at the bottom of the slab compared to the top. This indicates higher drying shrinkage of concrete near the top of the slab causing the slab corner to warp upward between day 0 and day 2 after paving.

4. Changes in LVDT measurement response to temperature and moisture variations

The collected data from the LVDTs were voltage variations corresponding to the slab vertical displacement. To get the relative slab vertical displacement, each LVDT voltage reading was subtracted from the reference voltage reading which represents the flat slab condition. However, it's quite difficult to decide the time of occurrence of flat slab condition. So the LVDT voltage reading corresponding to first zero-temperature gradient during the evaluation periods was selected as the reference reading. Thus, the actual pavement behavior could be studied based on the shape of the PCC slab at zero temperature difference. The subtracted voltage readings were then converted to displacement values based on the equation provided by the LVDT manufacturer (Omega Engineering Inc 2006).

The vertical displacements at different slab locations (corner, edge, and center) were obtained from the corresponding LVDTs. The vertical displacements of corner relative to center were computed to examine the movement of slab (downward or upward). Fig. 7 illustrates the

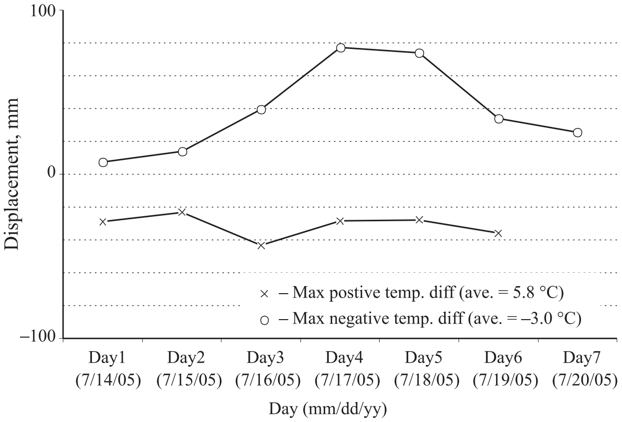

Fig. 7. Relative vertical displacement of slab at max temperature difference

relative vertical displacements of corner to center in slab 19. In this figure, a negative displacement value indicates downward movement of the slab while a positive value indicates upward movement of the slab. From the relative vertical displacement of corner to center, an upward movement of the slab is observed for negative temperature gradients (slab curls upward) while a positive temperature difference results in downward movement of the slab (slab curls downward).

Taking into consideration that the average max positive and negative temperature differences during field evaluation period were 5.8 °C and −3.0 °C, respectively, the relative vertical displacement at the max positive temperature difference should be higher than that at the max negative temperature difference. However, this could not be observed in this study. Therefore, the upward curling of the slab associated with negative temperature gradient appears to be more obvious in this study compared to the downward curl of the slab which is associated with a positive temperature gradient. This phenomenon may be related to a certain positive temperature gradient which results in flat slab condition.

A positive temperature gradient occurred between the top and the bottom of the pavement due to daytime construction and heat of hydration. Due to rapid drying of moisture in the exposed slab top, there might have been drying shrinkage of concrete near the slab top and a higher saturated condition at the slab bottom. This in combination with slower moisture movement through slab depth compared to temperature led to a flat slab condition at positive temperature gradient. This phenomenon has been commonly observed in previous research studies on PCC early age behavior and is referred (Rao *et al.* 2001; Rao, Roesler 2005; Yu *et al.* 1998). In addition, the concrete is still plastic and hence it is quite difficult to support the whole weight just by the slab corners (Byrum 2001). Therefore, when a zero temperature gradient occurs, the slab tends to curl upwards (Rao *et al.* 2001; Rao, Roesler 2005; Yu *et al.* 1998).

5. Changes in profile measurement response to temperature and moisture changes

The Rollingprofiler profile measurements were analyzed to confirm the trend in LVDT vertical displacements. The curvature of the slab measured by the Rollingprofiler, called as slab curvature profile in this study, was confounded with the construction slope and surface irregularities in the raw data of surface profile measurements. Currently, there does not seem to be a standard method to identify the curvature of the slab due to curling and warping from the raw surface profiling data. However, several procedures have been proposed to detect the slab curvature profile (Byrum 2001; Marsey, Dong 2004; Sixbey *et al.* 2001; Vandenbossche 2003) from raw surface profiling data. Among them, the similar procedure suggested by Sixbey *et al.* (2001) and Vandenbossche (2003) was used in this study.

A straight line from the first reading to the end reading of the raw surface profile curve was plotted. Each raw surface profile data point was subtracted from this linear line to remove the construction slope, and then normalized to the first measured profile data point to eliminate the effect of surface irregularities. In this manner, the slab curvature profiles were zeroed to first reading and end reading in a measured trace.

The diagonal slab curvature profile in test section 1 constructed using this procedure is displayed in Fig. 8 for illustration. The slab curvature profile measured in test section 1 clearly showed upward curling for the morning measurements and almost flat shape for the afternoon measurements. This behavior could be attributed to the permanent upward curling and warping resulting from the positive temperature gradients during setting time and to the negative moisture differences after setting time. The profile results for test section 2 could not be discussed here due to space constraints.

Comparisons between LVDT readings and slab curvature profile readings in test section 1 were conducted. The relative displacements of the corner to the center or the mid-edge in measured direction (R_c) were calculated as following similar procedure by previous researchers (Marsey, Dong 2004) and plotted with time as shown in Fig. 9. The upward movement at the slab corner is posi-

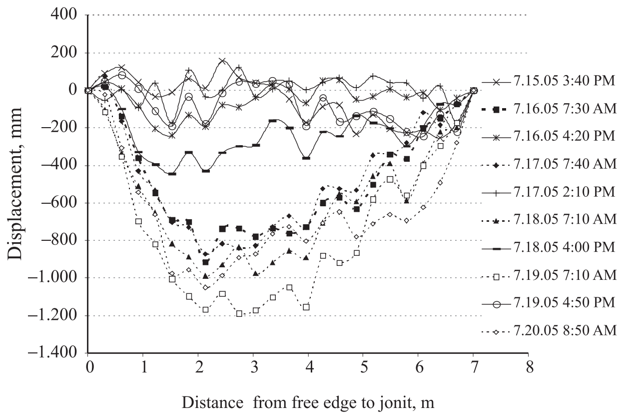

Fig. 8. Diagonal slab curvature profile

tive in Fig. 9. The R_c trends with time are similar for both LVDT measurements and slab curvature profiles. Especially, the upward curling of the slab is evident in both measured directions, indicative of the presence of permanent upward curling and warping during the field evaluation periods. Even though different slabs were used for LVDT measurements and surface profiling, it is interesting to note that the magnitudes of R_c calculated from slab curvature profile are higher compared to the LVDT measurements. However, this trend has been indirectly observed in previous research studies (Armaghani *et al*. 1987; Beckemeyer *et al.* 2002; Rao *et al*. 2001; Rao, Roesler 2005; Yu *et al*. 1998) which estimated temperature difference associated with flat slab condition with different slab curvature measurement techniques (using either LVDT or surface profile data).

In general, research studies (Armaghani *et al.* 1987; Beckemeyer *et al.* 2002; Byrum 2001; Rao *et al.* 2001) have reported higher temperature differences associated with flat slab condition based on surface profile measurements compared to those estimated from the LVDT measurements. The trends observed in this study are in agreement with the findings from previous research studies.

6. Summary of findings

A newly constructed JPCP on US30 near Marshalltown, Iowa, USA was instrumented to evaluate and study the early-age JPCP behavior in terms of pavement deflection with respect to temperature and moisture variations. The temperature and moisture data obtained from the field were analyzed. The slab deformation associated with temperature and moisture were measured and analyzed through vertical displacement and pavement surface profiles. The following are the findings of this study:

- during the first 8 h of paving, the average pavement temperature trends do not follow the air temperature trends. Although the air temperature decreases, the pavement temperature increases possibly due to the heat of concrete hydration. After the first 8 h of paving, the pavement temperature follows the air temperature with some phase lag;
- the temperature differences usually are positive at daytime and early night time and negative at late night time and early morning while moisture differences show the reverse trend. Especially, between day 0 and day 2 after paving, the moisture differences (between the top and bottom of the slab) are negative for most of the times resulting in a higher drying shrinkage near the top slab and then causing the corner of the slab to warp upward;
- the relative corner displacements from center or mid-edge (R_c) calculated from both slab curvature profile measurements and the LVDT measurements show similar trend. Both measurements show that the slab behavior during field evaluation periods tend to be mostly upward at the corner. This behavior can be attributed to the permanent upward curling and warping resulting from positive temperature gradients during setting time and negative moisture differences after setting time.

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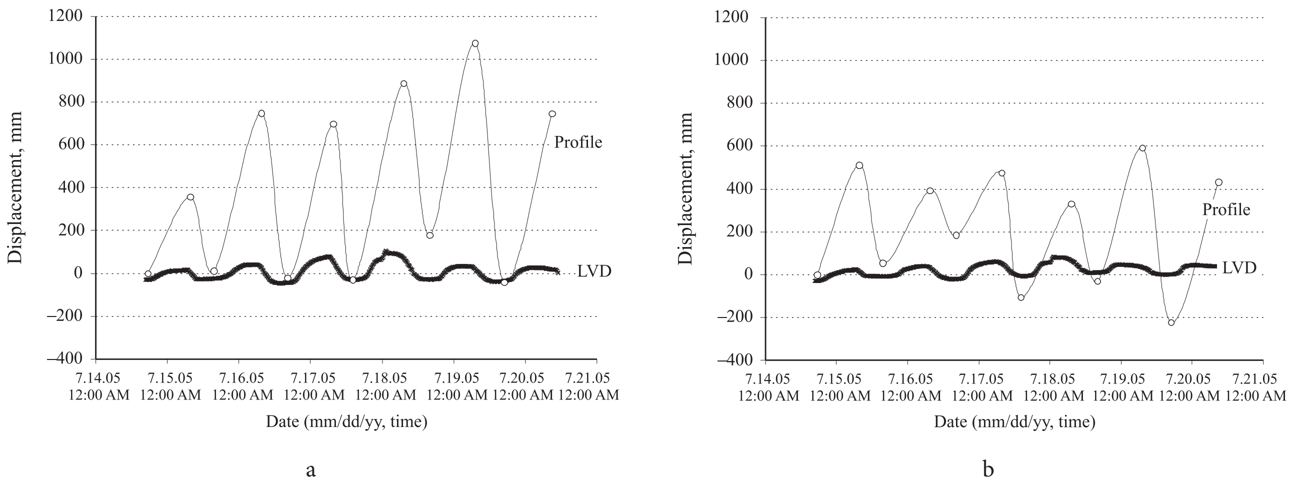

Fig. 9. The comparison of relative displacement of the corner (R_c) with time between LVDT measurement and slab curvature profile: a – diagonal direction; b – transverse direction

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