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Experimental analysis of curling behavior of continuously reinforced concrete pavement

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HIGHLIGHTS

- Curling displacements of CRCP under temperature variations are measured in situ.
- Curling behaviors of CRCP depend on vertical slab temperature gradients.
- Curling displacements are the largest at slab edge and the smallest at mid-slab.
- Curling displacements at the expansion joint are independent of the length of CRCP.
- Suggestions to minimize surface roughness due to curling of CRCP are proposed.

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ABSTRACT

This study investigates the vertical deformation called the curling of continuously reinforced concrete pavement (CRCP) and its relationships with crack spacing and temperature variation across the slab depth known as the temperature gradient. To this end, in-situ experiments are carried out at a full scale highway test section of CRCP. Two slab segments with different lengths (0.75 m and 2.0 m) and a free end expansion joint are chosen to cover a full spectrum of vertical slab movements that define the curling motions of CRCP. Test results showed that the slab segments and the expansion joint curled corresponding to the temperature gradient. The maximum curling displacements occurred along the shoulder side slab edges and those were prominent at the expansion joint and then at the transverse cracks. The curling displacements along the longitudinal joint side were smaller and those along the mid-slab were the smallest. The curling displacements at the expansion joint were not dependent on the length of CRCP. Although the curling motions of CRCP were not large enough to directly worsen the surface smoothness, suggestions were proposed to even improve the overall performance of CRCP.

1. Introduction

Portland cement concrete pavement (PCCP) expands and contracts in the horizontal plane under temperature changes, and at almost the same time both temperature and moisture content differences within PCCP bring about an out-of-plane distortion of slab. Although traditionally the distortion of slab from temperature gradients is called curling while the distortion from moisture gradients is called warping, the term ‘curling’ is used in this study since the moisture induced strains can be converted into the temperature induced strains. Depending on the directional properties of these temperature and moisture changes, there can be either upward curling (curl up) or downward curling (curl down) as depicted in Fig. 1. Since PCCP is normally restrained by its weight and the reaction from underlying layers, curling inevitably leads to the development of tensile stress in a concrete slab. If the slab materials cannot resist the maximum tensile stress, cracks would develop in the slab [1–9]. As demonstrated in some studies, this crack damage may be further deteriorated when PCCP is loaded with heavy traffic [10–13].

Among the most popular PCCP types, the joint concrete pavement (JCP) has regularly spaced contraction joints to minimize damages due to the expansion and contraction of its slab. However, these contraction joints are often linked to curling that in most cases affects the load transfer efficiency and pavement surface

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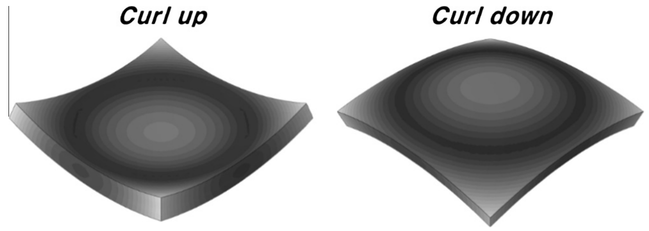

Fig. 1. Schematic of curling in PCCP.

smoothness [14–17]. Therefore, curling and its effect on the performance of JCP have been treated as one of key design and construction parameters [18,19].

In the continuously reinforced concrete pavement (CRCP), multiple transverse cracks develop and most of them penetrate the concrete slab vertically, yielding many divided slabs (hereinafter slab segments). Although the longitudinal reinforcing steels in CRCP still maintain their continuity, these slab segments may experience the curling motions under temperature changes. Moisture difference between top and bottom of slab can cause the curling as well, but it has to be accompanied by the temperature difference all the time. In other words, the temperature difference along the slab depth is a leading cause to the curling of CRCP, which may subsequently influence the surface smoothness, the load transfer efficiency between adjacent slab sections, and the performance of CRCP.

The purpose of this study is to investigate the temperature curling of CRCP and its relationships with the temperature variation across the slab depth and transverse crack spacing. To this end, a series of full-scale experiments was conducted at one of highway CRCP test sections constructed and instrumented in Korea. Using the measured data, the curling behaviors of CRCP along both the longitudinal and transverse directions were analyzed. The results of this study would lead to a better understanding of the CRCP curling and its potential influence on the surface smoothness and performance of CRCP.

2. Field experiment

2.1. CRCP test section

A series of field tests was conducted at one of three CRCP sections of the Korea Expressway Corporation Test Road (KECTR) in Korea [20]. The 360 m long CRCP sections were built in 2002 and were designed to represent a most common highway CRCP that is composed of 300 mm thick concrete slab placed on 150 mm thick lean concrete. A 50 mm thick asphalt bond breaker was placed between the concrete slab and lean concrete to separate them from each other. Since the CRCP section with a steel ratio of 0.6% shows somewhat irregular crack spacings compared to other two CRCP sections whose ratios of steel to concrete are 0.7% and 0.8%, this section was selected because of easy choice of different crack spacings for the test. It is noted that the steel bars are placed at the mid-depth of slab and the average crack spacings of the CRCP sections with steel ratios of 0.6%, 0.7% and 0.8% are about 1.6 m, 1.6 m and 1.2 m, respectively.

Field cores extracted at different post-construction stages have been confirming that most of transverse cracks penetrate the slab leaving multiple segments. In this study, two extreme slab segment sizes were chosen to cover a full spectrum of vertical slab movements that define the curling motions: 2.0 m (designated as L-slab) and 0.75 m (S-slab). The L-slab is a 2 m long × 0.3 m thick × 4.2 m wide discrete slab section. The S-slab is a 0.75 m long slab section that has the same depth and width as the L-slab. These two slab segments are far away from each other so any interference in the curling motions is prevented. Since the test section has an expansion joint, the curling behavior of CRCP at the free end is also evaluated. A CRCP that has a length of about 40 m from the expansion joint to the terminal anchor lugs is designated as E-40, and the other CRCP of about 320 m long from the expansion joint to the other side terminal anchor lugs is designate as E-320. It is noted that since the expansion joint in this CRCP section was formed by cutting the slab about 8 years after the construction to investigate the free end behavior of CRCP, the slab lengths from the expansion joint to the anchor lugs were intentionally designed to be significantly different.

2.2. Instrumentation and data collection

In each section, linear variable differential transformers (LVDTs) were installed to measure the vertical displacements of the slabs at selected locations. A total of 12 LVDTs were distributed along the transverse cracks, longitudinal joint, shoulder, and interior of L-slab as shown in Fig. 2. Seven curling paths are also allocated to observe the changes in vertical displacements across the section. It is noted that the LVDTs were mounted at the bars that were securely fixed at the base. For the shoulder side, LVDTs were installed after removing shoulder pavements and for the interior and longitudinal joint side, they were installed after making holes in the slab to fix the mounting bars into the base. Therefore, all the gages were isolated from the concrete slab.

Fig. 3 shows the seven LVDTs installed along the transverse cracks, longitudinal joint, shoulder, and interior of S-slab. Five curling paths are selected for the S-slab based on the LVDT layout for the curling analysis. Because of lack of the number of available LVDTs, it was decided that more LVDT were installed to measure displacements at the extreme locations of curling, which were the shoulder side and interior of slab.

Six LVDTs were installed along the free end expansion joint between E-40 and E-320 as shown in Fig. 4 to measure the vertical displacements at the free end and also to evaluate the effect of the CRCP length on the free end curling behavior.

Along with air temperatures, temperature variations inside of CRCP slab were collected at three depths (top, middle, and bottom) by installing thermocouples and i-Buttons [6,21] during the test period. The LVDT signals and temperatures were collected every 15 min.

3. Temperature gradient

Fig. 5 depicts the temperature variation through the depth of slab at every six hours during the experiments. All temperatures at 300 mm indicate the surface temperatures, while temperatures at 0 mm show the temperatures at the bottom of slab. At day times, temperatures at the top of slab are higher than those at the bottom of slab, but this is reversed at night times. The hourly temperature variation at the bottom of slab is small (6 °C–14 °C) compared to that at the surface (1 °C–28 °C). This temperature difference between the top and bottom of slab is the main cause to the curling motions (either curl up or curl down). The curl down is developed when the slab-top temperature is higher than the slab-bottom temperature normally when air temperature and solar radiation are higher at day times. As already depicted in Fig. 1, four slab corners sink and the slab center rises when the curl down takes place. The curl up takes place normally at night times when the slab-top temperature is lower than the slab-bottom temperature. Either curl up or curl down, the vertical distance between rising and sinking parts of slab can be used to quantify the vertical curling displacement.