

Development of a Portable Device for Measuring Curling and Warping in Concrete Pavements

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Abstract

Temperature and moisture variations across the depth of the Portland Cement Concrete (PCC) pavements result in a unique deflection behavior which has been recognized as curling and warping of the pavements since mid-1920s. The repeated slab curvature changes due to curling and warping, when combined with traffic loading, can accelerate fatigue failures including top-down and bottom-up transverse, longitudinal, and corner cracking. It is of paramount importance to measure the magnitude of curling and warping taking place in concrete pavements in order to develop performance measures and critical threshold magnitudes as well as gain a better understanding of their relationship to diurnal and seasonal temperature/moisture changes and pavement performance. Although several approaches have been proposed for this purpose for in-service pavements, they have certain limitations which inhibit their use for routine inspection for quality control and quality assurance. The primary objective of this study is to develop an economical and simple device for measuring curling and warping in pavements with accuracy comparable to the existing methodologies. Technical requirements are identified to establish assessment criteria for the proposed device. The detailed development and evaluation results for this device are presented and discussed with a focus on achieving reliable measurements in a cost-effective manner.

Introduction

It has been well known that climatic conditions have significant effects on pavement performance. Especially, moisture and temperature in concrete pavement structures are the two primary environmental drivers that can significantly affect the pavement layer and subgrade properties and, hence, its load carrying capacity. As the temperature and moisture varies across the depth of the Portland Cement Concrete (PCC) pavements, gradients develop to result in a unique deflection behavior that has been recognized as curling and warping since mid-1920s. The deflection

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resulting from temperature variations is referred to as curling and the deflection resulting from moisture variations is referred to as warping. Consequently, any force (e.g., self-weight of concrete, dowel bars, and friction between PCC slab and base course) that restrains the deflection will induce stresses within the slab (NCHRP 2004). The direction (upward or downward) and magnitude of developed slab deflection varies both diurnally and seasonally. However, due to long-term dry shrinkage, the PCC pavements in the field more exhibit upward deflection (Guo and Marsey 2001; Van Dam 2015).

The repeated slab curvature changes due to curling and warping, when combined with traffic loading, can accelerate fatigue failures including top-down and bottom-up transverse, longitudinal, and corner cracking (Hiller and Roesler 2005). While the impact of curling and warping on concrete pavements has been well recognized, there is no standardized method to measure them in practice. Various techniques have been explored through previous experimental studies including the linear variable differential transformers (LVDTs), digital indicators, profilers and laser-based technologies in order to measure the true degree of curling and warping of pavements. However, these approaches are not yet cost-effective, take long time to install/set-up/calibrate, and are complex to operate and perform data interpretation. All these limitations inhibit their use for routine inspections for quality control (QC) and quality assurance (QA) of concrete pavements.

Research Significance

Curling and warping plays an important role in concrete pavement design (e.g., thickness and joint spacing) and it has been drawing attention from transportation agencies since 1990s (Nantung 2011). However, due to the lack of specialized equipment and budget limitation, it is difficult to document the true degree of curling and warping in the field. The existing technologies/devices with potential to measure slab curls have their own limitations such as high device cost, inconvenience of operation, and are time and labor consuming. Hence, this research aims to develop a portable, simple, reliable, and economical device primarily for curling and warping measurements in concrete pavements with accuracy comparable to or better than the existing methodologies. It is expected that this proposed device from Iowa State University (ISU) can be used as a standard curling and warping measurement method in the field and thus lead to improvement of concrete pavement construction practices.

Review of the Currently Available Technologies/Devices for Measuring Slab Curling Behaviors

The currently available technologies/device used for curling behaviors are intended to measure surface profile or local displacement of PCC slabs. These include LVDTs, digital indicators, rod and level, straight edge, dipstick profiler, walking profilometer, Automated Laser Profile System (ALPS), and laser based inertial profiler which are compared in Table 1.

Linear Variable Differential Transducers (LVDTs). Installation of LVDTs prior to pavement construction to record vertical displacement probably is the most widely adopted method to investigate curling and warping behavior in the field (Lederle et al. 2011, Ceylan et al. 2005, Kim et al 2010, Rao and Roesler 2005). This displacement measurement sensor is suitable in high alkali environment due to electromagnetic coupling and it theoretically has infinite resolution. However, the cost of this method is high because many LVDTs should be installed on various location on

single PCC slab and the cost of a single LVDT unit is around \$500. Furthermore, the data acquisition system and the labor involved are quite expensive as well.

Digital Indicator. Digital indicator is a stationary measuring system capable of detecting tiny elevation changes at a single point from 0.002 mm. to 2.5 cm. It can be placed and suspended over the pavement surface to capture continuous pavement profile change if computer system is connected. However, this technology requires time-consuming setting up process and longtime road closure and therefore it can be used only in the limited period before traffic opening to investigate built-in curling and warping (Johnson et al. 2010).

Rod and Level. Rod and level offers a standard and simple way to accurately lay out a road. It basically measures the elevation of the target point according to a reference point. Because it is originally designed for true pavement surface profile measurement so it also can be used for curling and warping inspection. However, although this method is simple, it is also extremely labor-intensive (at least two people are required to carry out testing) and time consuming due to a very slow operation speed of less than 0.01 km/hr (ASTM Standard E1364-95 2012; Olson and Chin 2012).

Straight Edge. Straight edge is also a simple way widely adopted to inspect surface irregularities in road construction, particularly for rut-depth measurement on flexible pavement. Since it measures downward displacement of pavements, it can also be used for curling and warping measurements. The straight edge method utilizes an aluminum beam with certain length (1.7~5 m) and a measuring gauge to measure downward displacement between the beam and pavement surface. The main limitation is that the length of the straight edge is fixed and cannot be adjusted with different PCC slab lengths.

Dipstick. Dipstick is a typical hand-held inclinometer commonly used to measure a relatively small quantity of pavement profile and to calibrate other complex curling and warping measurement device due to its high accuracy (up to 0.127 mm). It also has been extensively used for curling and warping measurement in the field (Lederle et al. 2011) and it just requires one person for operation with 10 to 15 measurements per minute. However, the dipstick may miss some critical features due to its footpad spacing. The feature measured may be underestimated compared to other device because of sampling interval. The theoretical analysis conducted by Perera and Kohn (2005) indicated that sampling interval of the dipstick may cause features to contaminate the measurement due to aliasing if the wavelength is twice shorter than its normal sampling interval (Perera and Kohn 2005).

Walking Profilometer. Similar to inclinometers, the “walking” profilometer is also a kind of hand-held profiler which is widely used to quantify pavement profile for roughness measurement. A “walking” profilometer can measure the pavement surface profile by utilizing the diamond styluses, optical sensors, or accelerometers instrumented on the device. The profile will be recorded when the device is pushed by the operator at “walking speed” with a resolution up to 0.0025 mm (Morrow 2006). However, it is usually very expensive and its operation can be easily affected by surrounding environment.

Laser Technologies. Laser-based technologies have already been proved to be effective tools for pavement profiling. The recent achievements in mounting laser scanner on moving vehicle such as Automated Laser Profile System (ALPS) and inertial profilers provide effective ways for curling and warping measurement in a large quantity of pavements. ALPS was developed by Minnesota Road Research Project (MnRoad) in 2003 and its modified version, ALPS 2, is specially designed for curling and warping measurement.

ALPS 2 is a mobile low-speed profiling device with 4.6 m long ALPS aluminum beam mounted in front of a lawn tractor which can travel at a speed of 8 to 21 km/hr. The depth measurement is performed by high precision distance measurement laser sensors on the carriage with a resolution up to 0.0025 mm (Worel et al. 2003). Similarly, inertial profilers mounted by laser based height sensor have potential to be used for curling and warping measurement. The whole system also contains an accelerometer, speed/distance measuring system and corresponding computer system for calibration process. The main advantage of inertial profilers is its high operation speed (around 110 km/hr) which make it effective and its potential for adoption as a standard means for conducting network-level profile measurements by most highway agencies (Byrum 2001). However, this kind of profiler usually has very high initial cost (although its unit operation cost may be lower than other methods). Additionally, its results will not be accurate when the driving speed is less than 10 mph (Sayers and Karamihas 1998).

The measurement of actual degree of curling and warping taking place in concrete pavements is of paramount significance to develop performance measures and critical threshold magnitudes as well as gain a better understanding of their relationship to diurnal and seasonal temperature/moisture changes and long-term pavement performance. However, currently there is no standardized method applicable for curling and warping measurement in practice. According to Table 1, it can be easily seen that the majority of methods are quite expensive and involve complex procedures in calibration, operation, and data interpretation. The other cheaper methods are usually time consuming. Therefore, there is a critical need for the development of a simple, portable, economic, reliable, accurate, and rapid curling and warping measurement device. In order to develop such a portable device, the design criteria need to be identified first based on literature review results.

Table 1. Summary of currently available devices for measuring slab curling behaviors (price available until July 2015).

Device	Speed (km/hr)	Resolution (mm)	Road Closure Required	Price	Min. Number of People	Difficulty of Operation	Portable	Limitations
Rod and Level	0.01	0.127	Yes	\$240	2	Simple	No	• Intensive time and labor consuming
Straight Edge	0.08	1.5	Yes	\$150	1	Simple	Yes	• Cannot be adjusted with slab length due to fixed beam length
Dipstick Profiler	3.2	0.127	Yes	\$4,500	1	Medium	Yes	• No correlations with other methods
LVDT System	N/A	infinite	No	\$4500*	N/A	Medium	No	• Results are not reliable when sampling interval is short
Digital Indicators System	N/A	0.0025	Yes	\$1300*	N/A	Simple	Yes	• Have to be installed in pavement
Walking Profilometer	4	0.0025	Yes	\$30,000	1	Medium	No	• Fixed single point measurement
ALPS2	21	0.0025	Yes	\$10,000	1	Complex	No	• Installation and datalogger are costly
High Speed Profiler	110	0.025	No	\$50,000	1	Very Complex	No	• Usually used before traffic opening
								• Single point measurement
								• Time consuming installation
								• Easily affected by external factors
								• Complex data processing
								• Not accurate when speed < 16 km/hr
								• Difficult data processing
								• Still needs a reliable way to correlate its outputs with curling and warping

* Assume 3 LVDTs or digital indicators are used to measure deflection at slab corners and mid-edge (the price includes data acquisition systems as well)

Design Approach of the ISU Portable Curling and Warping Measurement Device

Curling and warping induced slab curvature is mostly upward in the field due to long-term dry shrinkage characteristics (Guo and Marsey 2001; Van Dam 2015). The upward curvature (most noticeable at the PCC slab corner) can be up to 2.5 cm and the cracking is usually not excessive when it's less than 0.64 cm (Suprenant and Malisch 1999). As a result, the newly designed device should be able to measure the curvature at least from 0.5 cm to 2.5 cm in the field.

Since the device is promised to be portable so it should be easily carried by just one adult, which means the weight of the device should not be heavier than 11 kg and the size of the device should be as small as possible. For rapid measurements, the measurement time should not be larger than 10 minutes to obtain 5 points for a concrete slab from the slab edge to another. However, those methodologies that do not require road closure typically involve expensive laser scanning or pre-sensor instrumentation. But, it is not mandatory requirement in this design. The summary of design criteria are listed as follows:

- Provide reliable deflection measurement
- Size should be small enough to be easily transported
- Weight is less than 10 kg
- Easy to operate without special training
- Quick set up and measurement (time $\leq$ 10 minutes)
- Enough resolution
- Available measuring range should be 0.5 cm. to 2.5 cm at least
- No complex calibration and calculation involved
- Low cost

Development of the ISU Portable Curling and Warping Measurement Device

Based on the design criteria developed, a new curling and warping measurement device was fabricated. The first generation prototype of this device is a static pavement deflection measurement instrument which sets up a tightened string over a concrete slab surface. The string is tied to two steel columns standing upright at the opposite slab joints for mid-chord deflection measurement at random intervals. However, the first generation device has some unnecessary features resulting in extra weight and size. As a consequence, some modifications were made to improve its portability.

Figure 1 illustrates an overall view of the modified device. It can be seen that the device mainly consists of two columns which are made of 0.38 m long, 50 mm×50 mm square hollow section steel tube. Aluminum rollers were pinned on the metal plates welded to the columns in order to adjust the string during measurement. For convenience, the column with two rollers (76 and 101 mm. in diameter, respectively) is referred to as “column A” and the column with just one roller (76 mm in diameter) is referred to as “column B”.

The larger roller in column A is a U-groove solid wheel equipped with a 100 mm long crank and there are ten small holes in total drilled on its flanges. Two same holes were drilled on the soldered metal plates as well. When the holes are adjusted in the same line by rotating the crank, a steel bar can be inserted to lock them together. Furthermore, the string shown in Figure 1 is made of stainless steel with 1.5 mm diameter which can hold up to about 250 kg weight. It is 9 m long and can be twined around the U-groove wheel and

hooked up by a spring hook if not used. As for the 76 mm diameter roller in column A, a small groove with just 1.5 mm in depth and width was cut to restrain the lateral motion of the string during measurement.

In column B, the roller pinned is exactly same as the 76 mm diameter one in column A. When the string is drawn to the roller in column B, it can be hooked up at the bottom of a bolt fastened by a handle at the head. The bolt can be moved up by adjusting the handle so the string will be tightened after the larger roller in column A is locked.



Figure 1. Overview of modified ISU curling and warping measurement device.

Both columns have two small feet at bottom to help keep the balance of columns at the edges in case of unevenness of pavement surface. Two small anchors were also soldered vertically underneath the bottom of the columns respectively, as shown in Figure 2 (a). These anchors are designed to be inserted into the joints so that the columns will be stuck in the joints to restrain their movement. Because a joint is usually cut to be 10~15 mm wide for cracking control and joint sealant so the anchor is about 6 mm in thickness. A cut was also made in the middle of the anchors to leave some space allowing the string pass through straight.

In addition to the columns, a right angle triangular measuring gauge was made to measure the mid-chord deflection, as shown in Figure 2 (b) and (c). The gauge has a step-shaped slope with 26 cm in length and 2.54 cm in height. The step-shaped slope is evenly divided into 20 scales in height and therefore the height difference of adjacent scales are 0.127 cm. The scales are marked from 1 to 20 where Scale No.1 represents 0.127 cm and Scale No.20 represents 2.54 cm in height.

Moreover, it is also realized that the string may not be pushed to the pavement surface hard due to pavement surface unevenness and sometimes the section in the middle of a slab may show downward curvature resulting a higher elevation than slab corners. As a result, some accessories including clips and small pins were used to help the measurement, which are the red pieces shown in Figure 2 (c). The clips can be placed under the bottom of columns to squeeze the string. The small pins are used to be placed under string near the two columns so the string can be heightened. In this way, the results measured with pins can eliminate the errors due to bumps or downward curvature in some parts of the slab that have higher elevations than the elevation two ends (column A and B).

After these modifications, this device has a total weight of about 10 kg. The height of two main columns are 0.38 m so they can be placed into a small bucket for transportation.

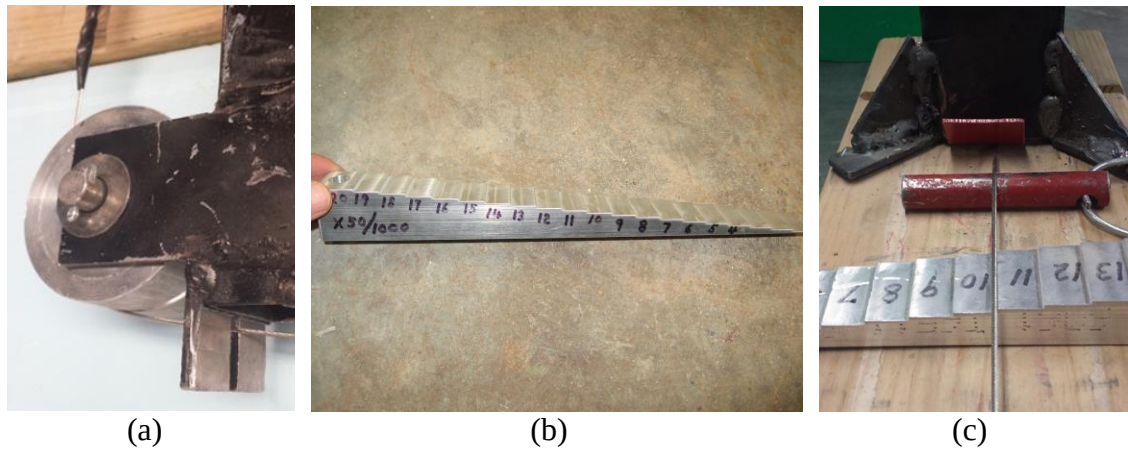


Figure 2. Modified ISU curling and warping measurement device.

Field Tests for Device Evaluation (October 24 and November 10, 2014)

Two field tests were conducted on October 24 and November 10, 2014, respectively, to evaluate the modified devices on a newly paved 3.7 m × 3.2 m PCC slab in a parking lot. Both morning and afternoon measurements were taken on each day to obtain the value under maximum temperature and moisture difference conditions. Figure 3 shows a picture of the modified ISU curling and warping measurement device in use in the field on November 10, 2014.

In the test on October 24, 2014, two small holes were made first in the middle of the joints to insert anchors of the columns. Then the string was hooked off from column A and drawn to pass through the roller in column B. The string was hooked up at the bottom of the bolt and then the steel bar was stuck into the hole of U-groove wheel in column A to lock it. After that, the string was tightened firmly by adjusting the handle in column B. In Figure 3, it can be seen that a measuring tape was spread out along the string to record the locations of measured points. The whole process of setting this up took about 4 minutes. Prior to measurements, pavement surface temperature and ambient relative humidity (RH) were recorded. The pavement surface temperature was 16.5 °C and RH was 93% in the morning while temperature and RH became 24 °C and 75%, respectively, in the afternoon on October 24, 2014.

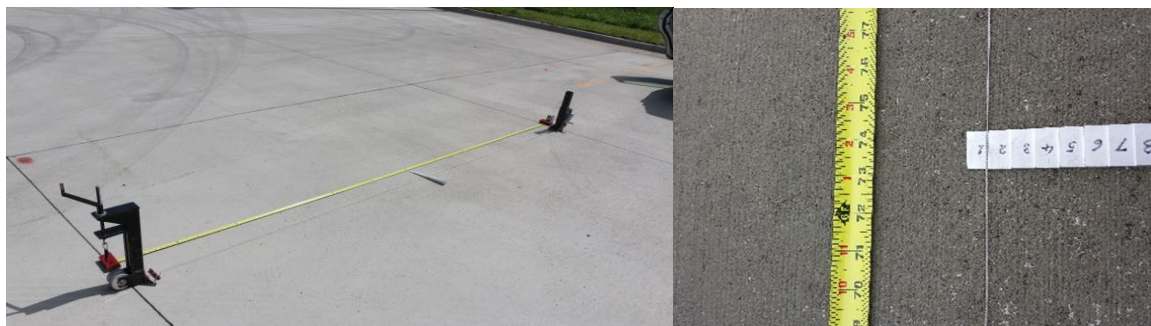


Figure 3. Field test on November 10, 2014.

It was recommended by ASTM E1364 that maximum measuring interval between two data points is 305 mm for Class 1 resolution (0.125 mm) and 610 mm for Class 2 resolution (0.25 mm) in terms of roughness assessment. For curling and warping, Class 2 resolution already satisfies the basic measuring requirements and so 610-mm interval is sufficient. However, in most cases, critical locations of curling and warping (e.g., slab edges and center) matters. So, five measurements nearby critical locations along the profile with even intervals are recommended in the field. However, in this study, the measurements were taken every 25 mm for device assessment purpose only. The measurement of one point just takes about 2 seconds and so it took less than 30 seconds to obtain typical five point measurements. The whole process took approximately 10 minutes.

The test on November 10, 2014 adopted the same procedures at same slab. Data were taken in the morning with 5 °C temperature and 80% RH. In the afternoon, pavement surface temperature was 13 °C and RH was decreased to 60%.

Figure 4 illustrates the curling and warping measurements taken in the morning and afternoon on the two days. According to Figure 4 (a) and (b), it can be seen that the slab indicated a left-skewed upward curvature on both days. On October 24, the maximum deflection was 0.13 cm for both morning and afternoon measurements. However, although the profiles measured in the morning and afternoon almost look same and overlapped each other in Figure 4 (a), more curls were still observed in the afternoon because 83 out of 146 measurements were on the x-axis in the afternoon compared with 75 out of 146 measurements on the x-axis in the morning. This phenomenon is fully in agreement with the general situation in the field where more warping occurs in the afternoon due to dry shrinkage.

Figure 4 (b) illustrates the pavement deflection measurements on November 10, 2014. It can be seen that the maximum deflection was increased to 0.25 cm, which shows a reasonable agreement with common sense that more curling and warping will be developed due to diurnal and seasonal temperature/moisture changes. Furthermore, the comparison of the morning and afternoon results indicates that diurnal changes of curling and warping does not vary too much. More instances of curling and warping happened in the afternoon as well which matched well with the observations on October 24, 2014.

The whole test took less than 15 minutes for 146 measurements and it took less than 5 minutes for typical five measurements, including setting up and data recording. The test results from the two days indicates some issues of the newly developed ISU curling and warping device to be improved:

- The triangular measuring gauge does have enough resolution which make it is difficult to capture slight deflection changes between nearby points in the newly constructed pavement
- The instrument can be modified to be smaller and lighter
- The anchor sometimes is a little hard to be inserted in the joints tightly due to thermal expansion of PCC slabs



(a)



(b)

Figure 4. Test results (a) on October 24, 2014; (b) on November 10, 2014.

Improvement of the ISU Portable Curling and Warping Measurement Device

Further improvements were made based on previous test observations. First of all, a digital height gauge was selected as the alternative measuring gauge considering its lower price (less than \$20), high resolution (0.01 mm), and convenient operation in the field. Figure 5 illustrates the comparison between the triangular measuring gauge and the digital height

gauge. Besides the measuring gauges, the height of column A and B were reduced to 0.3 m by shortening the columns and handle to further reduce the weight and size of this device (see Figure 6 (a)). The anchors were also cut in a certain angle and then abraded to be thinner (3 mm) so they could be easier inserted into the joint (see Figure 6 (b)).

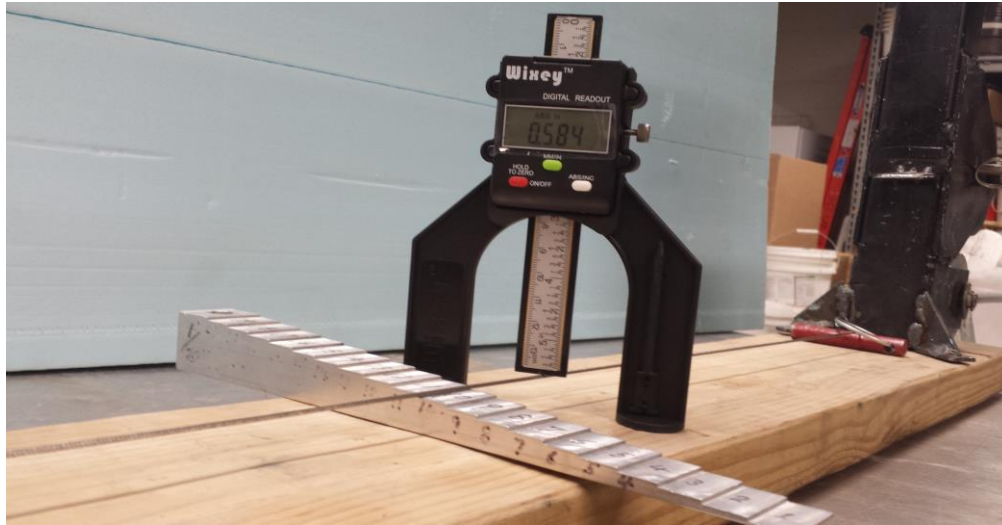


Figure 5. Comparison of measuring gauges.

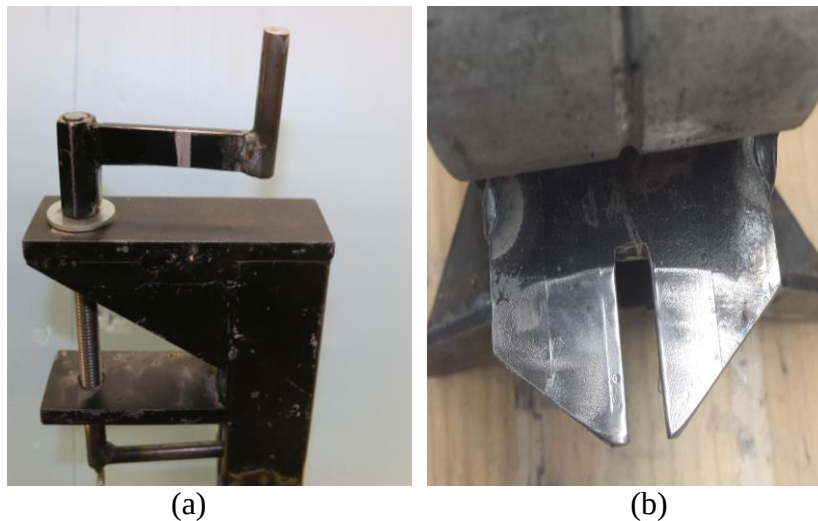
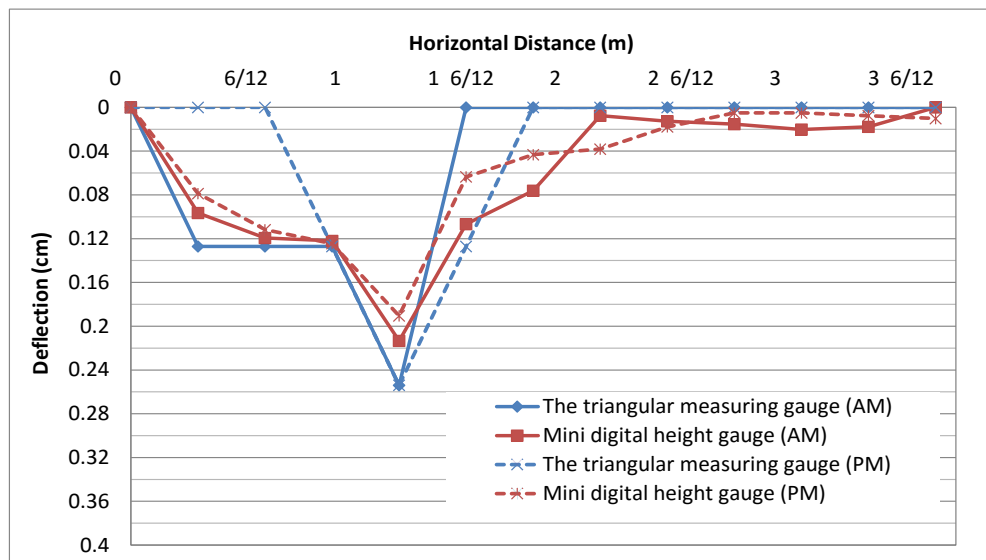


Figure 6. Enhancements of ISU curling and warping measurement device.

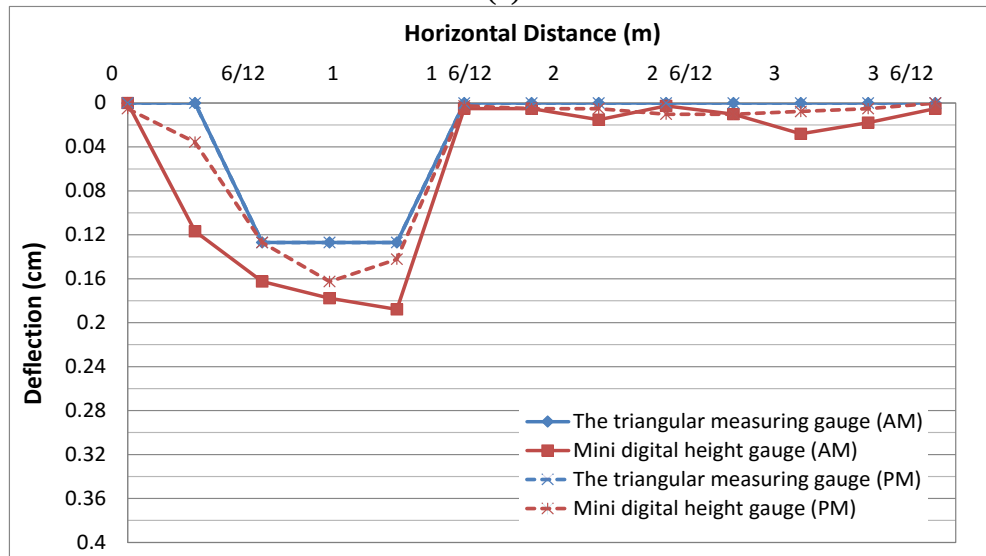
Field Tests for Device Evaluation (April 10 and June 20, 2015)

After these improvements to the device, another two field tests were conducted on April 10 and June 20, 2015 respectively to further assess the device. The test results are presented in Figure 7. The pavement surface temperature were 7.4 °C and 21 °C and RH were 61% and 37% for the morning and afternoon measurements on April 10, 2015, respectively. On June 20, the pavement surface temperature were 21.7 °C and RH was 78% while in the afternoon they became 29.4 °C and 68%. In these tests, both the triangular measuring gauge and digital height gauge were used to measure the mid-chord deflection. Moreover, the measurement intervals were 305 mm this time rather than 25 mm used before.

Figure 7 illustrates the captured pavement surface deflection profile. According to this figure, it can be seen the profile capture by digital height gauge has more reasonable shape due to higher resolution compared to the profile measured by the triangular measuring gauge. Furthermore, the profile is still left-skewed, which is coincident with the previous results. The maximum upward curls observed on April 10 were 0.25 cm by the triangular measuring gauge and 0.23 cm by the digital height gauge. On June 20, the measured maximum curls were 0.127 cm by triangular measuring gauge and 0.19 cm by the digital height gauge. Both figures illustrate that more curling/warping occurred in the afternoon. However, the maximum values measured on June 20 are smaller than the values measured on April 10, which is probably due to the heavy rain occurred in the early morning of June 20. The wetter bottom of pavement slabs resulted in the reduction of upward deflection due to induced downward curling and warping.



(a)



(b)

Figure 7. Field test results: (a) on April 10, 2015; (b) on June 10, 2015.

These tests validate the feasibility of using the digital height gauge for deflection measurement. The results indicate that it is able to provide fast and reliable measurements by using the finalized device for curling and warping measurement in the field. In general case, the time to take five typical measurements for pavement profiling is less than 1 minute in the field with a 4-minute setting up process. Typically, one operator is sufficient and no special training is required for the operation.

Summary

The primary objective of this study is to develop an economic, portable, easy to use, and reasonably accurate curling and warping measurement device which can be used for routine inspections of quality control (QC) and quality assurance (QA) of concrete pavements. The advantages of this device compared to other methods are listed as follows:

- This device has small size and relative light weight for convenient transportation to the field.
- This device has comparable and flexible resolution (can be 0.001 in. or higher), depending on the rulers used
- Compared to other available devices such as the rod and level and the straight edge, this newly developed ISU portable curling and warping measurement device has faster operation speed with no intensive labor requirement (only one operator required). Furthermore, this device is also much cheaper as well.
- Compared to profilers (both low speed and high speed profilers) and LiDAR system, the ISU curling and warping device is much more portable and easy to operate. No special training and/or software required for device operation, data processing, and results calibration.
- Compared to LVDTs and digital indicators based curling and warping measurement systems, the ISU portable curling and warping measurement device can be used without pre-installed sensing system, which are usually time consuming and labor-intensive. Furthermore, lots of LVDTs and digital indicators have to be used in order to obtain a comprehensive pavement deflection profile due to their single and fixed point measurement while ISU portable curling and warping measurement device can provide flexible measurement across the entire pavement.
- The device is a lot cheaper which is around \$320 compared to LVDT system (about \$3,000 at least for a single PCC slab, including installation cost and datalogger), digital indicator system (about \$2,000, including datalogger cost), profilers (about \$5,000 at least), and LiDAR system (over \$100,000, including software and data processing cost). The price of this device can be further reduced to just \$100 if it is produced in industrial scale.

In recent years, there has been an increasing need for a standard device that is not only portable and economical, but also simple and accurate for curling and warping measurements in in situ concrete pavements. The newly developed ISU curling and warping device can fill in this need. A series of recent field evaluation tests demonstrated such feasibility.

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