한국도로학회 논문집
第7券3號 2005年 9月
pp. 79 ~ 91

콘크리트 도로 포장의 초기 온도 분포 분석

Temperature Patterns in Concrete Pavements at Very Early Ages

김성민* 남정희**
Kim, Seong-Min Nam, Jeong-Hee

요지

포틀랜드 시멘트 콘크리트 도로 포장의 온도 패턴을 콘크리트 타설시부터 최근에 개발된 저렴하며 획기적인 센서를 이용하여 측정하였으며 그 결과를 분석하였다. 콘크리트 포장의 온도 측정은 여러 다른 지역에서 여러 다른 두께를 가진 콘크리트 포장에서 수행하였다. 콘크리트 포장의 온도 패턴은 깊이방향과 콘크리트 타설시간에 따른 종방향의 변화를 고려하여 분석하였으며, 포장 표면의 반사율, 그늘, 덮음막 등이 콘크리트 포장의 온도 패턴에 미치는 영향을 분석하였다. 본 연구 결과에서 콘크리트를 타설한 날의 콘크리트 포장의 최고 온도는 종방향을 따라 타설 시간이 다름으로 인해 생기는 차이가 두드러지는 것을 알 수 있었다. 콘크리트의 영점응력온도(zero-stress temperature)는 타설한 날의 최고 온도와 직접적인 연관이 있으므로 타설 시간에 따른 최고 온도의 차이는 콘크리트 포장의 거동 및 성능에 크게 영향을 미칠 수 있다. 또한 콘크리트 포장의 표면 상태(표면 색상, 그늘 유무, 덮음막 유무 등)도 콘크리트 포장의 온도 패턴에 큰 영향을 미치는 인자인 것으로 분석되었다.

핵심용어 : 콘크리트 포장, 콘크리트 온도, 덮음막, 그늘, 표면 반사

Abstract

The temperature patterns in Portland cement concrete (PCC) pavements were measured and comprehensively analyzed from the beginning of the concrete placement based on the temperature measurement technique developed using innovative and inexpensive temperature measurement sensors. The temperature measurements in PCC pavements were taken at several different locations forvarious slab thicknesses. The concrete temperature patterns in the vertical and longitudinal directions of the pavement were analyzed and the effects of the pavement surface reflectivity, shading, and covering on the concrete temperatures were evaluated. The results of this study showed that the significant differences in the maximum concrete temperatures on the placement day were observed according to the concrete placement time. Since the zero-stress temperature is a function of the maximum concrete temperature on the placement day, the placement time would be an important factor that affects the behavior and performance of concrete pavements. The surface conditions of the pavement, such as the surface color, shading, and covering also affected the temperature patterns in PCC pavements significantly.

Keywords: concrete pavement, concrete temperature, covering, shading, surface reflectivity

---

[*] 정회원 · 경희대학교 토목건축대학 조교수 · 공학박사
[**] 미국텍사스 오스틴 주립대학교 박사후연구원 · 공학박사

1. Introduction

Portland cement concrete (PCC) pavements are used on highways with high traffic volumes and large trucks due to their load carrying capacity and durability. Unfortunately, concrete pavements constructed during excessively high temperatures and/or high evaporation conditions can lead to close cracking and moisture loss levels in the pavement that substantially reduce the serviceable life of the pavement. Spalling due to moisture loss or punchouts in continuously reinforced concrete pavement (CRCP) caused by close cracking can be so severe that major rehabilitation might be required in less than ten years on pavements designed for 30 years. For those rehabilitation projects, the cost to the public can be substantial as illustrated by two cases in Houston, Texas, USA, where a bonded concrete overlay was required on a section of a state highway (BW-8) with a cost over US$6 million dollars, and an asphalt overlay on another state highway (SH-6) with a price tag over two million dollars required on a section of SH-6 (Trevino, 1996; Chavez et al., 2003a, 2003b Trevino et al., 2004). Traffic delay and other user costs due to the premature rehabilitation would add more to the total cost.

Generally, initial cracking in PCC pavements is highly correlated to the temperature patterns in the concrete. Since the restraints, such as the frictional bond between the concrete slab and the base in both jointed concrete pavement (JCP) and CRCP and the reinforcement in CRCP, exist in the concrete slab, the concrete will experience tensile stress in direct proportion to the temperature differential experienced before it has reached full strength, and also in proportion to the absolute difference between the zero-stress temperature(the temperature at which the concrete experiences no stress) and the eventual minimum temperature reached, usually in the winter after placement. The higher the temperature differential, the higher the stress. The higher stress results in successive cracking until the stress has been relieved to a point below the tensile strength of the concrete and no more cracking occurs.

Engineers have known for some time the detrimental effects of high temperatures and excessive moisture loss, but have not been able to monitor them in an acceptable fashion(McCullough et al., 1999). Although the low temperature of the pavement is determined by the weather and cannot be controlled, the high temperature at which the concrete sets or reaches the zero-stress state can be monitored and used as a prediction of the pavement' s ultimate performance. This is useful for both quality control (if the contractor has real time access to the information) and quality assurance performance specification. Recently, some innovative and inexpensive devices have become available to monitor pavement curing conditions and help reduce the small number of pavements that will not reach their design life due to conditions during construction. This paper presents a field test program to measure the temperature in concrete pavements, a development of a measuring device, and a comprehensive analysis of the temperature patterns in concrete pavements.

2. Measurement device and field tests

The Thermochron i-Buttons manufactured by Dallas Semiconductor have been employed to measure concrete temperatures. The Thermochron i-Buttons are dime-sized devices that contain a computer, network interface, storage, a battery, and a temperature sensor.

These devices can be programmed to record the temperature at any desired time interval. They can internally store 2048 readings of temperatures (for instance, they can hold about 28 days of temperature data with every 20-minute reading, or about 170 days of temperature data with every 2-hour reading). The battery in the Thermochron lasts more than a few years. The data can be downloaded into any standard laptop or palm computer using software provided by the manufacturer. Since the Thermochrons are inexpensive (about US$16 each), monitoring of temperatures in the concrete pavement can be achieved in an economical way.

In order to measuretemperatures at desired depths of the concrete slab, the holes slightly larger than the diameter of the Thermochron were made in the plexiglass probes at the desired depths and the Thermochrons were inserted in the holes and epoxied to withstand immersionin concrete. These Thermochron i-Button assemblies were installed in the concrete pavement, as shown in Fig. 1, just after concrete placement but before tinning operations. Since each Thermochron has its own serial number, the Thermochrons can be connected to each other in parallel using wires. Therefore, as shown in Fig. 1, only two wires are needed to download the data regardless of the number of the Thermochrons attached in the assembly.

In-situ measurements of concrete pavement temperatures have been conducted using the Thermochron i-Button assemblies in several different locations in the state of Texas, USA. Those locations include Austin, Houston, Baytown, Cleveland, and Van Horn. The temperature data was collected from the beginning of the construction. About 180 Thermochrons were installed in the pavement in those test sections. In each test section, the measurements were taken at various longitudinal locations of the pavement as well as at various depths of the pavement to comprehensively identify the temperature patterns in the concrete pavement. The failure ratio of the sensor was less than 1% during the first month after concrete placement and about 20% after one year of construction.

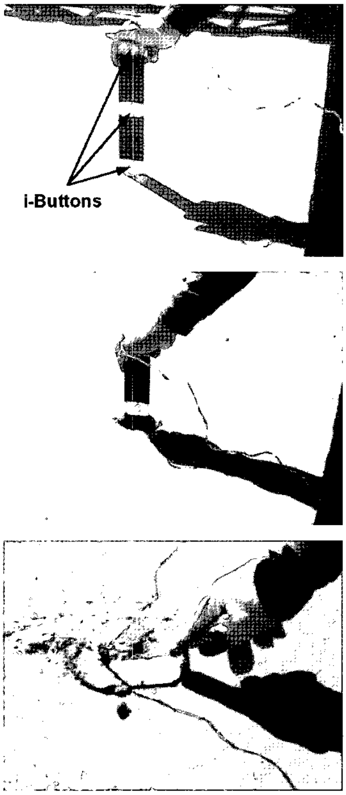


Fig. 1. Installation of Thermochron i-Buttons in the concrete pavement.

3. Concrete temperature variation in the vertical direction

The time histories of the concrete temperatures at the top, mid-depth, and bottom of the concrete slab are shown in Fig. 2 from the beginning of the concrete placement time for ten days. The data was collected at the Cleveland test section and the concrete placement time was at 11 a.m. In the figure, the concrete temperature at the top represents the temperature collected from the Thermochron installed at 2.5cm (1 in.) below the surface of the concrete slab. Similarly, the bottom temperature represents the concrete temperature at 2.5cm (1 in.) above the bottom of the concrete slab. As shown in the figure, the pattern of the concrete temperature at the top is similar to that of the air temperature, but the concrete temperature is higher than the air temperature. The daily concrete temperature variation is the largest at the top and the smallest at the bottom. The daily peak temperature (maximum or minimum) occurs at the top first and then time delays to the daily peak temperatures are observed at other depths. This lag becomes larger as the depth from the top increases. Since the concrete temperature at the top is much affected by the air temperature, the concrete temperature at the top is the highest in the daytime and the lowest at night, except for the concrete placement day. On the placement day, the concrete temperature is affected not only by the air temperature but also by hydration heat of concrete generated during the concrete curing process. As a result, the highest concrete temperature on the placement day can occur at any depth, not always on the top of the slab, depending on the air temperature variation and the amount of hydration heat. As can be seen from the figure, on the placement day, the maximum concrete temperature occurs at the mid-depth, and the maximum temperature at the top is clearly lower.

The typical daily cycle of the concrete temperature profile through the depth of the concrete slab is shown in Fig. 3. The results shown in the figure illustrate the variation of the temperature profile through the slab depth for 24 hours on the 12th day after concrete placement. The concrete was placed at 7 a.m. in the Cleveland test section. After sunrise, the concrete temperature begins to increase and the increment is the largest at the top and the smallest at the bottom (see data from 7:30 to 16:30 in the figure). As the air temperature drops after sunset, the top temperature begins to decrease but the bottom temperature still increases for a while and then finally begins to decrease(see data from 19:30 to 7:30 in the figure). The maximum temperature gradient through the depth in the daytime(occurred at 16:30 in this case) is clearly larger than the opposite signed maximum temperature gradient occurred in the early morning (occurred at 7:30 in this case).

The concrete temperature profile through the slab depth for a few days after placement is different from the typical profile pattern described above due to

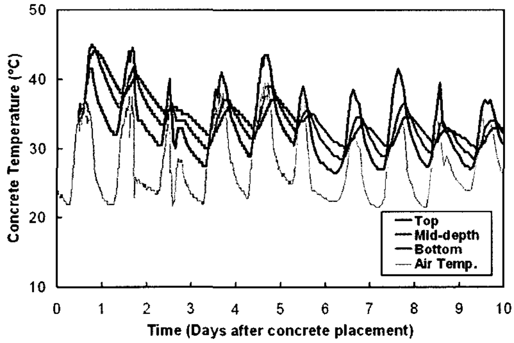


Fig. 2. Time histories of concrete temperatures at different depths

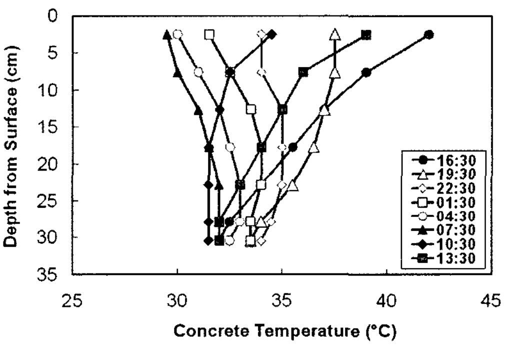
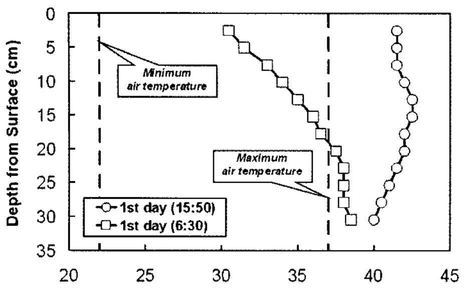
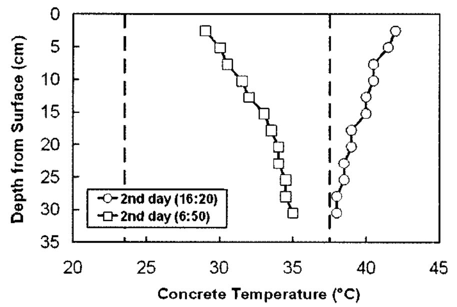


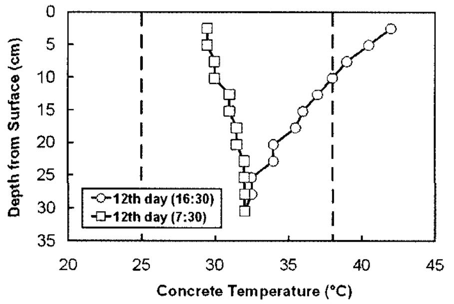
Fig. 3. Daily cycle of concrete temperature profile through the slab depth



(a) on the placement day



(b) on the second day



(c) on the 12th day

Fig. 4. Concrete temperature profile when the temperature at the top is at its daily maximum and minimum value

hydration heat of concrete. Fig. 4 shows the concrete temperature profiles on the placement day, second day, and the 12th day after the concrete placement when the concrete temperature at the top of the slab is at its daily maximum or minimum temperature. On the placement day, as shown in Fig. 4(a), when the top of the slab is at its maximum temperature, the temperatures near the mid-depth are higher. The temperature gradient through the slab depth is larger when the top of the slab is at its minimum temperature around sunrise. With time, as shown in Figs. 4(b) and 4(c), the temperature gradient through the depth when the top of the slab is at its maximum temperature becomes larger and that when the top of the slab is at its minimum temperature becomes smaller. Finally, the temperature gradient when the top of the slab is at its maximum temperature is larger than that when the top of the slab is at its minimum temperature. This phenomenon happens because the daily maximum or minimum concrete temperature at the top of the slab remains almost the same due to the close daily maximum or minimum air temperature as shown in the figure, but as time passes by, the concrete temperature at the bottom of the slab when the temperature at the top is at its daily maximum or minimum temperature becomes lower.

4. Concrete temperature variation in the longitudinal direction

On the concrete placement day, the air temperatures at the time of concrete placements will change as the placement progresses. The differences in the air temperature histories at different longitudinal locations will affect the temperatures of the concrete pavement in the very early age because hydration heat of concretegenerated in the very early age is dependent on the time history of the air temperature. The Thermochron i-Button assemblies were installed along the longitudinal direction as the paving process proceeded to investigate the concrete temperature variation along the longitudinal direction of the pavement. The placement time of the paving day was used as the control for the longitudinal location rather than the longitudinal distance.

The time histories of the concrete temperatures at several different longitudinal locations are shown in Fig. 5. The data shown in the figure was collected at the top of the concrete slab in the Austin test section. Since about 50m (164 ft) of concrete was placed in an hour, the longitudinal distance between the placement times of the 2-hour interval shown in the figure is approximately 100m (328 ft). The significant differences in the concrete temperatures among the locations with different placement times are observed on the paving day. The maximum concrete temperature on the paving day decreases as the time of placement becomes later on the day in this case. As the pavement becomes older, the temperature differences among the different placement times decrease. From several days after the concrete placement, the daily minimum temperatures are basically the same among the different placement times, but there are slight differences in the daily maximum temperatures, which might have resulted from the slightly different surface conditions such as textures and colors of the surface that govern the rate of the absorption of solar radiation. The effects of surface conditions on the concrete temperatures are explained later in this paper.

Fig. 6 shows the variationsin the difference between the temperatures of the concrete slab at the top placed at 8:00 a.m. and 2:00 p.m. as time goes by. In the *x* and *y* coordinate system, if the *x* and *y* axes are the temperatures at the 8:00 a.m. and 2:00 p.m. placementlocations, respectively; the relationship between them can be obtained by plotting the temperatures at the same collection times. If the temperatures at those two locations are identical, the slope of the graph will be 1 (45 degree linear line between the two axes) and the R^2 value will be 1 (all data is on the linear line and no scattering around the line). As shown in Fig. 6, the slope of the linear trend line between the temperatures at the 8:00 a.m. and 2:00 p.m. placement locations is initially less than 1 (the temperatures at 8:00 a.m. placement location are higher than those at 2:00 p.m. placement location), but the slope becomes close to 1 rapidly as time passes by. The R^2 value also becomes close to 1 as the pavement age increases, which implies that scattering of the data around the linear trend line becomes smaller and the differences in the concrete temperatures between the two locations with different placement times decrease, as the pavement gets older.

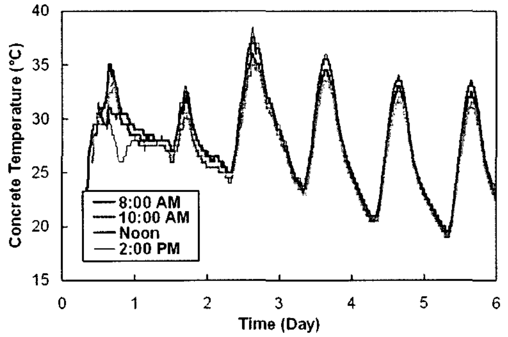


Fig. 5. Concrete temperature variation depending on the time of placement

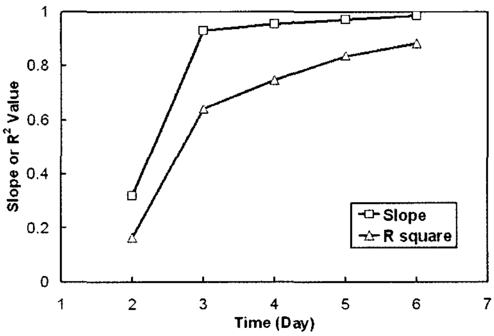
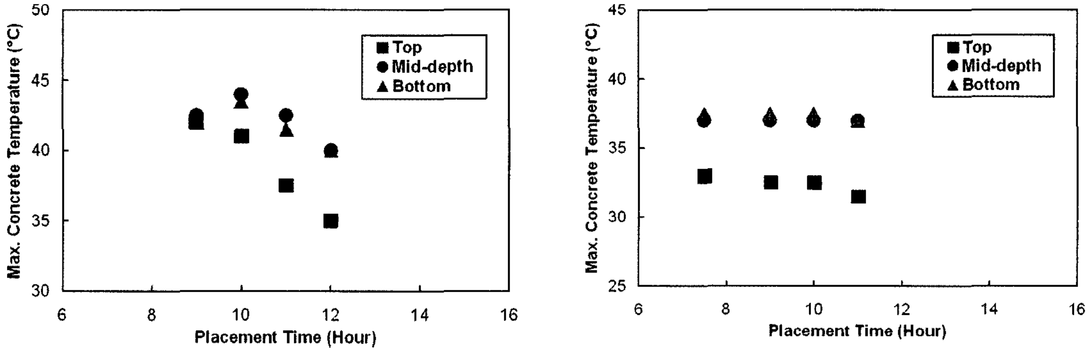


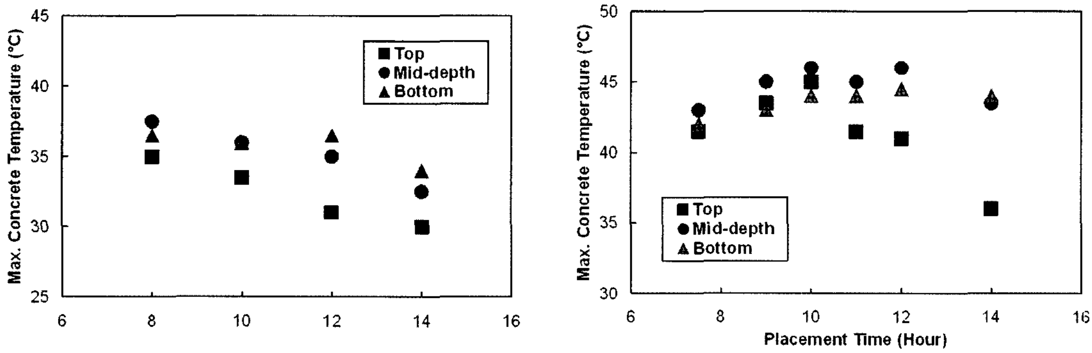
Fig. 6. Differences in concrete temperatures between 8:00 AM and 2:00 PM placement times

Fig. 7 shows the relationship between the maximum concrete temperature on the concrete placement day and the concrete placement time obtained from various test sections. The maximum concrete temperature on the placement day is different depending on the placement time as already mentioned. Normally, if the concrete is placed in the morning, the time of the maximum hydration heat occurrence and that of the maximum air temperature occurrence become closer, and as a result, the concrete temperature goes up higher. On the other hand, if the concrete is placed in the afternoon, the air temperature begins to drop while hydration heat generates, and as a result, the concrete temperature cannot go up significantly high. In the Baytown test section(Fig. 7(b)), however, since the air temperature variation was very small on the placement day, the temperature differences among the placement times at a given depth were very small. In most of the test sections, the placement day' s maximum concrete temperature at a given location (or placement time) is the lowest at the top of the slab and those at the mid-depth and at the bottom of the slab are close to each other. As pointed previously, since the maximum concrete temperature on the placement day is mostly affected not only by the air temperature but also by hydration heat of concrete, normally the maximum temperature does not occur at the top of the slab on the placement day. Since the zero-stress temperature is a function of the maximum concrete temperature on



(a) Houston

(b) Baytown



(c) Austin

(d) Cleveland

Fig. 7. Relationship between maximum concrete temperature and placement time on paving day obtained at the test sections

the placement day(Schindler, 2002; Kim et al., 2005), the placement time would be an important factor that affects the pavement behavior and performance.

5. Effect of surface reflectivity

The color of the pavement surface is slightly different from location to location because of several reasons such as variations in the rate of curing compound applications. The differences in the pavement surface colors can cause the different absorption rates of solar radiation, and result in different concrete temperatures. Tests have been conducted on the concrete pavement and small concrete specimens to investigate the effect of the surface reflectivity(or color) on the concrete temperature. For the test with small concrete specimens, concrete was poured into three small rectangular containers that have dimensions of 30 cm(12 in.) long, 23 cm(9 in.) wide and 4 cm(1.5 in.) deep, and the Thermochron i-Buttons were installed in the middle of the specimens. The surface of each specimen was then sprayed with paint. Three different colors of white, gray, and black were used in the test. As shown in Fig. 8, the concrete temperatures at night times are almost the same regardless of the surface color, but those at day times show significantly large differences among different surface colors. The daily maximum concrete temperature is the lowest in the white colored specimen and the highest in the black colored specimen. In this case, the differences in the maximum concrete temperatures were about 6 to 8℃ between white and gray and 12 to 18℃ between white and black colored specimens. Since a brighter color has a higher reflectivity, the absorption rate of solar radiation and the resultant temperature increase are smaller with a brighter colored specimen.

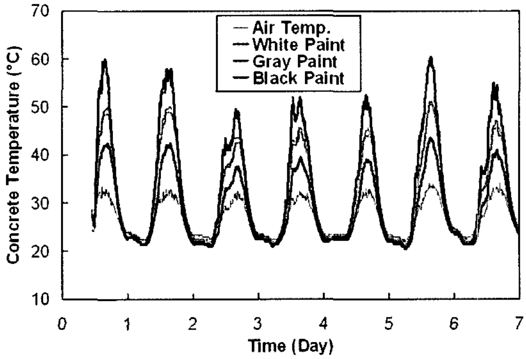
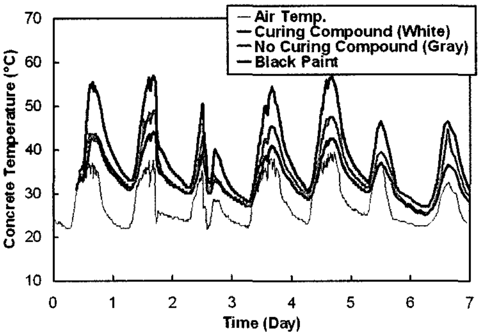
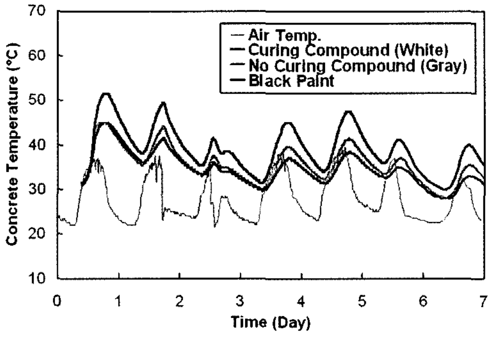


Fig. 8. Concrete temperatures with different surface colors

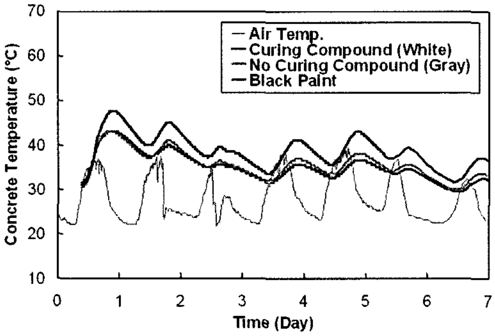
The effect of the surface reflectivity on the concrete temperature in the concrete pavement was also investigated. Two small square areas(1.2m by 1.2m) of the concrete pavement surface were kept covered with plastic sheets while white curing compounds were sprayed on the pavement and the cover was removed just after the curing compound application. The areas without the curing compound application showed the concrete color that was gray. One area of the two was then sprayed with black paint. The temperature measurement sensors were installed in the pavement at the areas of the white(normal curing), gray, and black colored surfaces. Fig. 9 shows the concrete temperatures at the top, mid-depth, and bottom of the slab for the three different colored pavements. At daytime, the black colored pavement shows the highest concrete temperatures and the white colored one the lowest, which is the same result obtained with the small specimens. Even in night times, the black colored pavement shows slightly higher temperatures. The temperature differences among the different colored pavements become smaller as the depth increases. The daily maximum concrete temperature differences at the top, mid-depth, and bottom of the slab between the white and gray colored pavements are about 3 to 8, 2 to 3, and 1 to 1.5℃, respectively, and those between the white and black colored pavements are about 10 to 14, 5 to 9, and 4 to 7℃, respectively, in this case. On the placement day, the difference intemperature between gray and white sections was minimal. This happens because the gray colored pavement does not have any curing compound on the surface and as a result the loss of heat due to evaporation makes the concrete cooler.



(a) at top



(b) at mid-depth



(c) at bottom

Fig. 9. *Differences in concrete temperatures among different surface colors*

6. Shading effect

Providing a shade immediately after the concrete placement could reduce the concrete temperature and the zero-stress temperature under hot weather conditions by decreasing the amount of solar radiation. To investigate the effect of the shade on the concrete temperature, tests have been conducted on the concrete pavement as well as with small specimens of concrete. For the test with small concrete specimens, two specimens were made and curing compounds were sprayed on the surface of both specimens. A shade was provided over one specimen and the other specimen was placed under direct sunlight. Fig. 10 shows the results of the test. The daily maximum concrete temperatures are significantly lower in the specimen with a shade. In this case, the difference in the concrete temperature ranges from 6 to 10℃. At night times, the specimen with a shade shows slightly higher temperatures (about 1.5℃ in this case). Therefore, it has been found

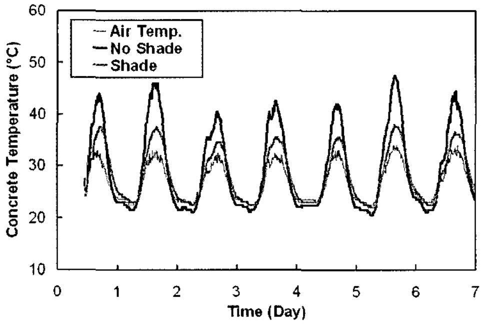
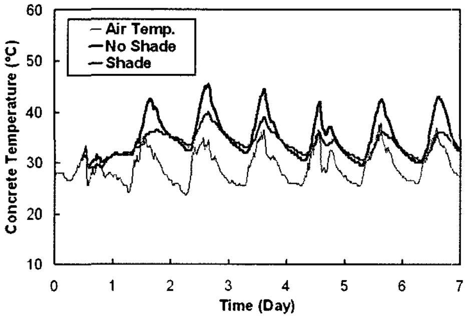


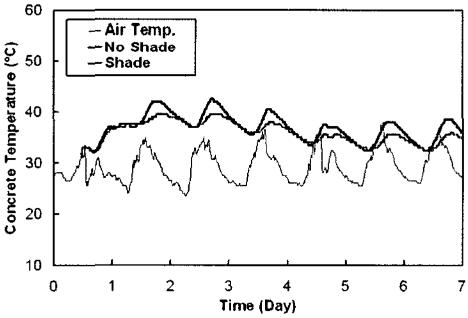
Fig. 10. Shade effect on concrete temperature in small specimen

that the daily concrete temperature variation decreases significantly when a shade is provided on the concrete specimen (about 7.5 to 11.5℃ in this case).

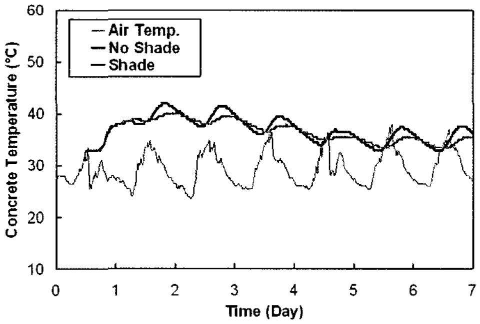
The effect of the shade on the concrete temperature was also investigated with the concrete pavement. A part of the concrete pavement surface (1.2m by 1.2m) was shaded and the concrete temperatures there were compared with those measured under direct sunlight.



(a) at top



(b) at mid-depth



(c) at bottom

Fig. 11. Shade effect on concrete temperature

Fig. 11 shows the concrete temperatures at the top, mid-depth, and bottom of the slab with and without shade collected in the Baytown test section. If the pavement is shaded, the daily maximum concrete temperature becomes much lower and the daily minimum concrete temperature becomes slightly higher. This implies again that the daily temperature variation is much smaller if the shade is provided. The decrements of the daily maximum concrete temperatures at the top, mid-depth, and bottom due to the shade are about 6, 3, and 2℃, respectively, in this case. In other test sections, the shade effect was also investigated and the results showed that about 5℃ of the daily maximum concrete temperature could be reduced with the shade at the top of the slab. The results obtained with the actual concrete pavement are basically the same as those obtained with the small concrete specimens.

7. Covering effect

If rain is expected during concrete placement, the pavement is covered by the polyethylene sheet to prevent damages from rainfalls. To investigate the effect of the cover with the polyethylene sheet on the concrete temperature, tests have been conducted on the actual concrete pavement and with small concrete specimens. For the test with small concrete specimens, a specimen was covered with the polyethylene sheet as soon as the specimen was made, and placed under sun light with the other specimen that was not covered. As shown in Fig. 12, the daily maximum concrete temperatures are significantly higher in the specimen with the polyethylene sheet cover. In this case, the differences in the daily maximum concrete temperatures between the two are mostly about 6 to 10℃. The maximum difference can be observed on the first day, which is 19℃. This large difference happens because in the specimen with the cover, heat generated by concrete hydration and solar radiation is mostly kept in the specimen and evaporation cooling is limited. The daily minimum concrete temperatures in both specimens are almost the same.

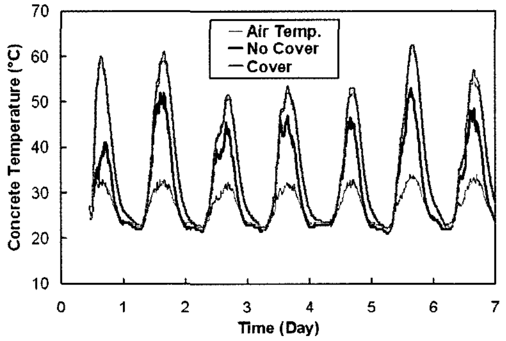
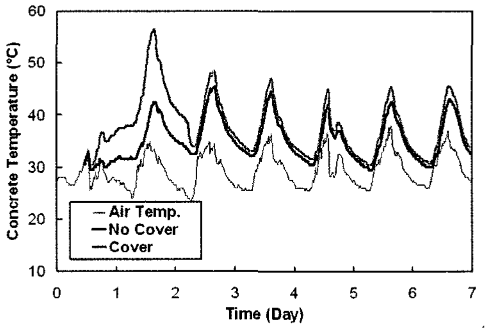
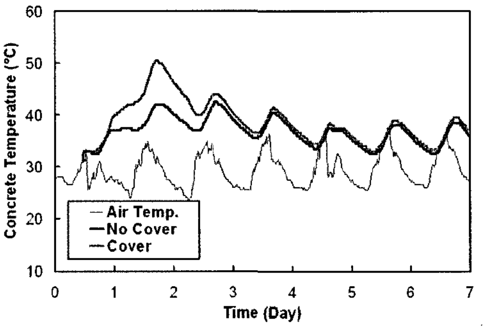


Fig. 12. Covering effect on concrete temperature in small specimen

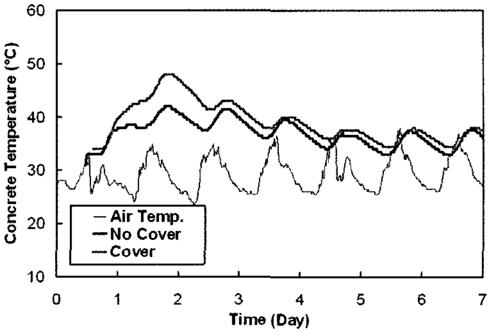
In the Baytown test section, because the weather changed suddenly from sunny to rainy about 2 p.m. on the concrete placement day, the pavement constructed after about 1 p.m. was covered by the polyethylene sheet to prevent rainfall damages. The concrete temperatures under the polyethylene sheet could be measured since a Thermochron i-Button assembly was installed at the location of the 1:30 p.m. concrete placement, which was covered by the polyethylene sheet. The polyethylene sheet cover was removed two days after the concrete placement. Fig. 13 shows the concrete temperatures at different depths of the slab with and without the polyethylene sheet cover. During the first two days after the concrete placement when the polyethylene sheet cover was applied, the concrete temperatures are much higher in the pavement with the polyethylene sheet cover compared with those in the pavement without the cover. The maximum concrete temperatures at the next day of paving are about 14, 8, and 6℃ higher at the top, mid-depth, and bottom of the slab, respectively. Even after the cover was removed, the concrete temperatures are still slightly higher. Since the zero-stress temperature is normally determined on the concrete placement day, the temperature increase because of covering makes the zero-stress



(a) at top



(b) at mid-depth



(c) at bottom

Fig. 13. Covering effect on concrete temperature

temperature higher. This could result in higher concrete stresses when the temperature drops. Therefore, if the polyethylene sheet cover is necessary, it should be removed as soon as possible to avoid a significantly large temperature build-up in the concrete slab.

8. Summary and conclusions

The temperature patterns in Portland cement concrete pavements were measured and comprehensively analyzed from the beginning of the concrete placement based on the temperature measurement technique developed using innovative and inexpensive temperature measurement sensors. The temperature measurements were taken at several different locations in Texas, USA, in PCC pavements with various slab thicknesses. The concrete temperature patterns in the verticaland longitudinal directions of the pavement were analyzed and the effects of the pavement surface reflectivity, shading, and covering on the concrete temperatures were evaluated. The results of this studypoint to the following conclusions.

- The devices developed for concrete temperature measurements using the Thermochron i-Buttons have been tried many times in the field and give very reliable readings. Since the installation of the devices in the concrete slab and the temperature data acquisition from the devices can be done easily, they can be implemented for the temperature management of the concrete pavement.
- The pattern of the concrete temperature at the top of the slab is similar to that of the ambient air temperature, but the concrete temperature is higher than the ambient air temperature.
- The daily concrete temperature variation is the largest at the top and the smallest at the bottom of the slab. The daily peak temperature(maximum or minimum) occurs at the top first and then the time delay to the daily peak temperature at another depth, which becomes larger as the depth from the top increases, is observed.
- On the concrete placement day, the highest concrete temperature throughout the depth of the concrete slab can occur at any depth, not always on the top of the slab, because the concrete temperature is affected not only by the air temperature but also by hydration heat of concrete generated during the concrete curing process.
- The maximum concrete temperature gradient through the slab depth on the concrete placement day occurs when the top of the slab is at its minimum temperature, but as time goes by, that occurs when the top of the slab is at its maximum temperature.
- The differences inthe concrete temperatures among the different concrete placement times decrease as the pavement becomes older. The significant differences are observed on the concrete placement day. Normally, the maximum concrete temperature on the placement day is higher at the morning placement locations than that at the afternoon placement locations. Since the zero-stress temperature is a function of the maximum concrete temperature on the placement day, the placement time would be an important factor that affects the behavior and performance of concrete pavements.
- Regardless of the surface color of the pavement, the concrete temperatures at night times are almost the same, but those at day times show significantly large differences among different surface colors.

The daily maximum concrete temperature decreases as the color of the pavement surface becomes brighter, because a brighter color has a higher reflectivity and a lower absorption rate of solar radiation. Therefore, the use of very bright white colored curing compounds can reduce the maximum concrete temperature and the zero-stress temperature on the concrete placement day.

- If the pavement is shaded, the daily maximum concrete temperature becomes significantly lower and the daily minimum concrete temperature becomes slightly higher. This means that the daily concrete temperature variation is much smaller if a shade is provided. Therefore, under very hot weather conditions, if a shade is provided on the placement day, the zero-stress temperature can be reduced considerably.
- If the pavement is covered by the polyethylene sheet, the concrete temperatures are much higher compared with those for the pavement without the cover. Therefore, if the polyethylene sheet cover is necessary to prevent damages from rainfalls, it should be removed as soon as possible to avoid a significantly large temperature rise in the concrete slab.

Acknowledgment

This research was supported by the Kyung Hee University Research Fund in 2005(KHU-20050380). The authors also express gratitude to Drs. Moon C. Won, Young-Chan Suh, and Soo-Ahn Kwon for their valuable comments.

References

1. Trevino, M. (1996). "Rehabilitation of Beltway 8 Pavement Spalling with Concrete Overlays." *Master' s Thesis,* The University of Texas at Austin, Austin, TX.
2. Chavez, C. I. M., Dossey, T.,and McCullough, B. F. (2003a). "Updated Status of the Continuously Reinforced Concrete Pavement Database in Texas: Imporvements and Trends." *Report 1778-2,* Center for Transportation Research, The University of Texas at Austin, Austin, TX.
3. Chavez, C. I. M., McCullough, B. F., and Dossey, T. (2003b). "Assessment of Data Collection and Supplementary Tasks Conducted for the Texas Rigid Pavement Database." *Report 1778-4,* Center for Transportation Research, The University of Texas at Austin, Austin, TX.
4. Trevino, M., Kim, S. M., Smit, A., and McCullough, B. F. (2004). "Decision Tree for Asphalt Concrete Overlays on Continuously Reinforced Concrete Pavements." *Report 4398-3,* Center for Transportation Research, The University of Texas at Austin, Austin, TX.
5. McCullough, B. F., Zollinger, D. G., and Dossey, T. (1999). "Evaluation of the Performance of Texas Pavements Made with Different Coarse Aggregates." *Report 3925-1,* Center for Transportation Research, The University of Texas at Austin, Austin, TX.
6. Schindler, A. K. "*Concrete Hydration, Temperature Development, and Setting at Early-Ages.*" Ph.D. Dissertation, The University of Texas at Austin, Austin, TX.
7. Kim, S. M., Nam, J. H., Dossey, T., Suh, Y. C., Claros, G., and McCullough, B. F. (2005). "A New Methodology for Concrete Pavement Quality Control Using Temperature and Moisture Measurement Techniques," *Proceedings of the 84th Annual Meeting of Transportation Research Board,* TRB, National Research Council, Washington, D.C. (CD-ROM).

〈접수 : 2005. 6. 20〉