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ASSESSMENT OF ASPHALT CONCRETE PAVEMENT QUALITY BY USING INFRARED THERMAL IMAGING TECHNOLOGY

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Key words: infrared thermal imaging technology, manhole, temperature, pavement.

ABSTRACT

Manholes cause uneven pavements, which affect the quality of pavement services, leading to public criticism in Taiwan. Many manholes are buried beneath pavements to ensure evenness and enhance the usability of pavements for pedestrians. The presence of manholes affects the quality of the asphalt concrete underneath the pavement because then conducting excavations using road construction equipment becomes difficult, ultimately leading to early deterioration of the pavement surfaces. Temperatures can also differ considerably between the manhole and non-manhole locations on asphalt concrete pavement. This study used infrared thermal imaging technology and an analysis of variances statistical method to investigate the differences in temperature changes at manhole locations. This technology can obtain accurate and detailed information on surface temperatures. The results reveal that the asphalt concrete in manhole and non-manhole areas will exhibit temperature differences of approximately 24-58°C, thus allowing for more accurate positioning of manholes during construction. In addition, this infrared thermal imaging technology can be used to determine pavement construction quality base on temperature uniformity of the asphalt concrete. Thus, infrared thermal imaging technology provides an optimal and cost-effective solution for constructing and maintaining pavements.

I. INTRODUCTION

In Kaohsiung, Taiwan, manholes are a major cause of uneven road surfaces. The total number of manholes of different sizes is approximately 220,000, an average of one manhole cover for every 6 m of road. Of these manhole, 41% belong to China Telecom, 30% belong to Taiwan Power Company, and 10% access tap water systems. Roads in metropolitan areas often will have many manholes that can affect the quality of road maintenance and leading to grievances. Thus, positioning manholes under the road surfaces so as to reduce adverse effects on traffic becomes a crucial and necessary policy. However, after the manhole covers are installed underneath the pavement surfaces, damages to construction manholes still occur from the poor quality of that construction work. Damage to manholes is generally detected using metal detectors; thus, identifying nonmetallic manholes during pavement excavation processes becomes difficult.

Over the years, infrared thermal imaging technology has been used for nondestructive detection by road management to assess the quality of asphalt concrete construction, with some success. However, when this technology is used to measure the location and size of asphalt concrete subsurface cavities, the time required for that measurement as well as variations in measured temperatures are affected by the strength and thickness of the asphalt concrete, the depth and size of the cavities, the thickness of the subbase, and the presence of steel in the asphalt concrete.

Lee (2008) used infrared thermal imaging technology to determine the location and size of cavities and discovered that when pixel numbers are used to calculate subsurface cavity sizes, the time required to compute variations in temperature differences increased with the thickness of the concrete. He suggested that the thickness of the concrete influenced the time required for obtaining a thermal image and that thermal imaging technology could detect the location and size of a subsurface cavity.

Li (2010) studied possible factors that affected the application of infrared thermal imaging technology to traditional wall painting, for example, the materials used for mural painting, and the pigments, colors, environmental humidity, and salt content. He suggested that the materials used for mural painting, as well as environmental humidity, and salt content had appreciable effects, whereas pigments and colors had smaller effects (Lee, 2008). Applying light-colored coating on

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road surfaces would enhance reflectivity; however, that reflectivity would decrease as the surface aged. The ground temperature would decrease by approximately 5°C for each increase of 0.1 in reflectance.

Chen et al. (2012) discovered that thermal cameras can be used to determine the construction quality of asphalt concrete pavements to manage roads. Asaeda and Ca (2000) indicated that the temperature increase for asphalt was greater than that of other pavement materials during summer, mainly because of the low reflectivity of asphalt and the differences in its thermal conductivity. The black color of asphalt is one reason that heat is absorbed during the day and large amounts of heat energy are released at night. Pavement materials with low thermal conductivity heat the pavement surface, while materials with high thermal conductivity will increase nighttime temperatures.

Yavuzturk et al. (2005) indicated that the surface temperature of asphalt can range from 0.9 to 6.6°C and that the thermal conductivity coefficient of asphalt materials will fluctuate between 0.5 and 2.5 W/mK. As the thermal conductivity increases with an increase in the surface heat dissipation rate, the asphalt surface temperature will also increase. A change of 1 W/mK in the thermal conductivity of typical asphalt materials causes a change of approximately 3.3°C in their surface temperatures. Chen et al. (2007) discovered that at surface temperatures below 50°C, the indirect tensile strength of asphalt considerably increased. The pavement temperature for open traffic was approximately 50°C. The indirect tensile strength at a pavement temperature of 50°C was approximately 2.7 times higher than that at 80°C. Chou and Lee (2013) further investigated the influence of manhole covers on road safety by considering three different coefficients of friction in order to test the skid-resistance characteristics of 99 manhole covers. The results indicated that most older manhole covers are not skid resistant, whereas newer manhole covers have high skid resistance; hence, the older covers should be replaced.

Chou et al. (2013) determined that manhole covers have low slip resistance when they are wet. After analyzing a variety of samples, they concluded that a checkerboard design will provide high skid resistance to manhole covers on roads. Maria et al. (2013) assessed the thermal properties of pavements by considering thermal parameters as emissivity, albedo, and the a solar reflective index. They observed that the slow release of internal heat within concrete during the day results in the concrete being hotter than bituminous materials. The reflectance and cooling effects of bituminous materials and concrete indeed differ, and this difference should be considered in the design and management of pavements and for determining the coating used for other surfaces to reduce the urban heat island phenomenon.

The studies on temperature changes at manhole locations are limited. This study used infrared thermal imaging technology to assess the changes in temperature during the preparation of asphalt concrete and also the temperature changes at actual manhole locations. Further, the temperature changes around manholes were compared to identify temperature changes that were typical to manhole locations, and the effects of temperature on pavement quality were also investigated.

II. MATERIALS AND METHODS

This study used infrared thermal imaging technology to detect changes in temperature during the preparation of asphalt concrete and also compare changes in the temperature of that concrete. A NEC F30S infrared thermal imager was used. Infrared thermal imaging is based on the principle that an object's surface at a temperature above absolute zero radiates infrared energy; the hotter the object, the more infrared energy is radiated. Infrared thermal imaging uses an optical device that can collect the infrared energy radiated by an object and transfer that energy to a sensor. The sensor then converts that energy into electronic signals, and those signals are amplified and displayed. The technology can detect temperature rapidly, and it allows the temperature distribution to be visually observed. Moreover, because the designated object is directly observed from a considerable distance, human injury is avoided. In addition, thermal imaging does not damage the pavement.

Asphalt concrete is extremely sensitive to temperature changes. If asphalt concrete exhibits high thermal uniformity during the paving process, rolling compaction is ensured, and the quality of the pavement is enhanced. In contrast, a conventional infrared temperature-sensing gun can detect the temperature of pavement only in a pointwise manner. It cannot effectively determine the temperature of the overall asphalt concrete pavement. This study used infrared thermal imaging technology to solve the problems frequently encountered in asphalt concrete pavement detection during the paving process, such as the influence of manhole covers on the actual pavement.

Using this detection technology, this study examined the heat transfer from manhole covers to the asphalt concrete above the cover after open traffic. The uniformity of the temperature distribution of the aggregates of the pavement and the influence of the manholes on asphalt concrete pavement were also examined. An analysis of variance (ANOVA) F-test was then used to compare the estimates of group variances to determine whether significant differences did exist between the sets of gathered data. ANOVA was used as an inferential statistical method to compare temperatures during the compaction of asphalt pavements. Further, the temperatures of covered and uncovered asphalt mixtures during transportation were compared.

III. RESULTS AND DISCUSSION

1. Changes in Pavement Temperatures

This study used infrared thermal imaging technology and color differences to represent the different gathered temperatures, and different color strengths to express the temperature

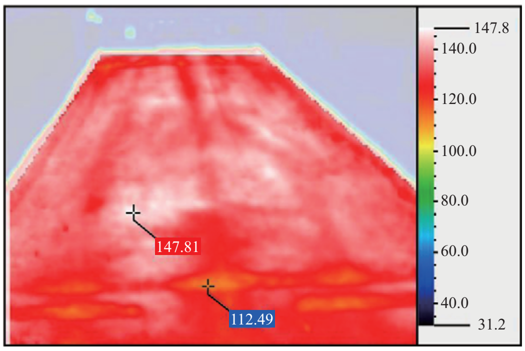

Fig. 1. Thermal image when paving using asphalt concrete.

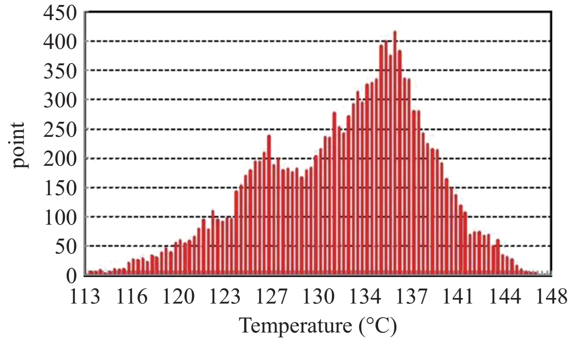

Fig. 4. Temperature chart when paving.

Fig. 2. Field comparison when paving.

Fig. 3. Detecting with infrared temperature-sensing gun.

ranges. Fig. 1 offers a thermal image diagram, and Fig. 2 presents a field comparison photograph. As these figures show, when asphalt concrete pavement is visually observed, any temperature differences cannot be clearly determined. Fig. 3 offers a photograph of the infrared temperature-sensing gun that was used to detect the temperature. As mentioned, an infrared temperature-sensing gun can detect the temperature of asphalt concrete, but only in a pointwise manner. Obtaining accurate data and determining the section or area that corresponds to the minimum temperature is difficult. However, infrared thermal imaging technology can facilitate the issue by clearly detecting temperature changes in paving.

Because asphalt concrete is sensitive to temperature, construction specifications require paving temperature to be at least 120°C. If the temperature is too low, the paving quality is low, potentially affecting the pavement negatively after open traffic. The maximum and minimum temperatures in Fig. 1 are 147.81 and 112.49°C, respectively. Inadequate rolling compaction and the aggregate segregation phenomenon, which is observed around the minimum temperature, will cause a decline in the stability of the asphalt concrete and lead to cracking problems during open traffic. Fig. 4 offers a statistical chart generated by the infrared thermal imager, which illustrates the regional temperature of a selected road. Here the vertical axis represents the temperature distribution at different points, while the horizontal axis represents the temperature in degrees Celsius. Because low temperature affects the temperature uniformity of asphalt concrete pavements, the difference in the temperature distribution reaches 35°C, and the maximum number of temperature distribution points is observed at 136°C. Another peak value appears at 127°C, and a slightly uneven temperature distribution becomes evident. However, if these temperatures were detected using a conventional infrared temperature-sensing gun, any uneven temperature distribution would be difficult to verify.

2. Thermal Image Analysis of Manhole Covers during Paving

Fig. 5 depicts the thermal image of the asphalt concrete temperature above a manhole cover before rolling compaction. Clearly, the manhole cover did not affect the temperature of the asphalt concrete pavement above the manhole. No apparent temperature decrease was observed. However, as Fig. 6 shows, the temperature of the pavement above the manhole cover decreased significantly after rolling compaction. Indeed, before rolling compaction, the aggregates were loose, so there were numerous pores in the aggregate particles. This scenario produces a low temperature convection speed, despite the asphalt concrete pavement being in contact with the manhole cover. The contact area between the pavement and the manhole cover was relatively small; therefore, the effect of the manhole cover on the temperature reduction rate was also relatively small. Consequently, no significant temperature difference was observed on the pavement.

However, after rolling compaction, the contact area between the manhole cover and the asphalt pavement increased, and thus the endothermic influence of the manhole cover

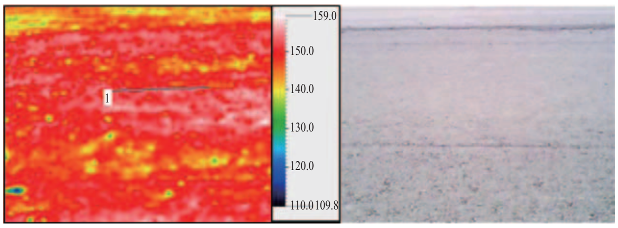

Fig. 5. Thermal-imaging analysis on a manhole location before initial rolling compaction.

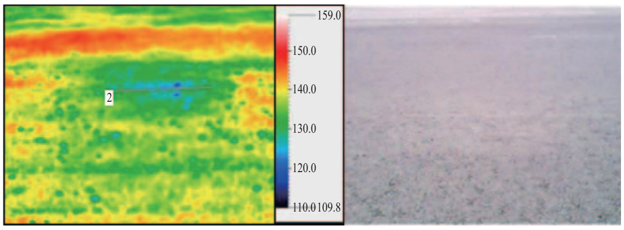

Fig. 6. Thermal-imaging analysis on a manhole location after initial rolling compaction.

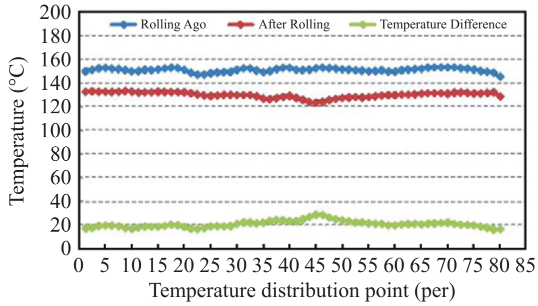

Fig. 7. Comparison of temperature differences at manhole location before and after rolling compaction.

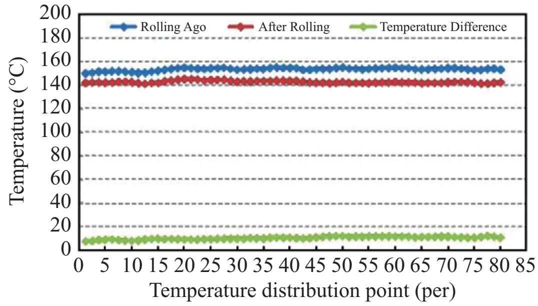

Fig. 8. Comparison of temperature differences at a location without a manhole before and after rolling compaction.

became apparent. The temperature convection speed among the aggregates also increased after rolling compaction. As a Consequence, an apparent temperature reduction at the surface of the asphalt concrete pavement was observed, as illustrated in Fig. 6.

Fig. 7 shows a comparison of the temperatures at the manhole location before and after rolling compaction, while Fig. 8 shows a similar comparison at a location without a manhole before and after rolling compaction (the temperature is plotted on the vertical axis, and the temperature distribution at different points is plotted on the horizontal axis). In Fig. 7, the temperature difference at the manhole location before and after rolling compaction shows as being between 20 and 30°C, whereas in Fig. 8, the temperature difference at the location without a manhole before and after rolling compaction shows as approximately 15°C. Therefore, we can infer that the rate of temperature decrease at the manhole cover location after compaction was high, and the range of the temperature difference distribution was relatively large. This finding demonstrates that when a manhole cover is located under an asphalt concrete pavement, the rolling temperature of the pavement above that manhole is insufficient and the temperature distribution is uneven, thus making it difficult to control the pavement quality. Manhole covers on an asphalt concrete pavement are indeed susceptible to damage.

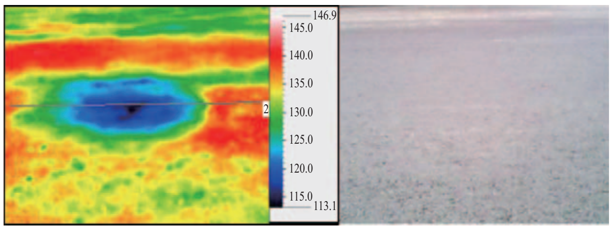

Fig. 9. Thermal imaging while paving above manhole cover.

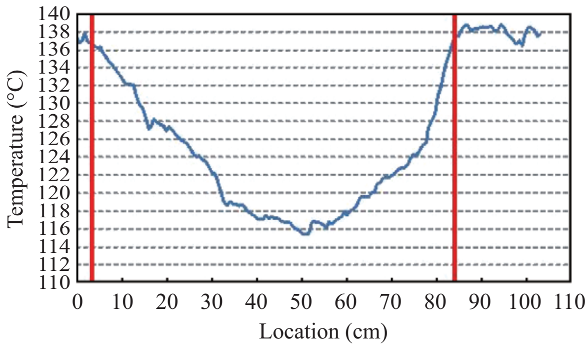

Fig. 10. Thermal imaging analysis while paving above manhole cover.

3. Thermal Image Analysis after Pavement Construction

Figs. 9 and 10 show the thermal image analysis results for the condition of asphalt concrete that is paved over manholes. The figure reveals that the presence of manhole covers underneath the asphalt concrete pavement led to a decreased in the temperature on the surface of the asphalt concrete pavement at the location of the manhole covers, with temperature decreasing about 10-20°C. The thermal image in Fig. 9 further shows that the temperature of the pavement around the manhole was relatively low and distributed in a square frame because a square concrete structure was constructed under the

Table 1. Analysis of temperature variations around manhole covers.

Relevant variables	Variable sources	SS	MS	*F*	*P*-value
Before & after rolling	among groups	22019.33	22019.33	661.47	6.06E-29
Manhole & without manhole before rolling	among groups	2449.74	2449.74	89.19	2.43E-12
Manhole & without manhole after rolling	among groups	9780.09	9780.00	175.20	2.69E-17
Manhole & without manhole for open traffic	among groups	384.17	384.17	1198.36	6.90E-10

asphalt concrete pavement around the manhole. When the asphalt concrete pavement is placed over this square concrete structure, the thickness of the asphalt concrete pavement must not be too thick. Hence, this range of the asphalt concrete pavement is relatively thin, leading to the thermal storage effect on the asphalt concrete pavement being less significant. Consequently, the temperature decreased.

In addition, thermal imaging revealed that the temperature increased positively with the distance from the manhole cover center because iron manhole covers can absorb heat from the pavement above them. The manhole tunnel underneath a cover is dark and damp, increasing the cooling rate of the temperature above. However, because there is no direct contact between a manhole cover and the ground, the heat absorbed by the manhole cover is not transferred directly to the bottom of the tunnel. The manhole cover radiates heat from the center outward, resulting in the heat absorbed by the pavement being emitted outward. Thus, the overall temperature of asphalt concrete above the manhole cover is reduced.

Fig. 10 corresponds to Fig. 9 and shows that the two edges of the manhole cover are located at 4 and 84 cm. The maximum temperature was approximately 139°C and was observed above the asphalt concrete pavement close to the manhole at locations 88 and 95 cm. The lowest temperature observed over the center of the manhole cover at 52 cm, at approximately 115°C, indicating a difference of approximately 24°C. The temperature was low at the center of the manhole because the airflow under the manhole created a cooling effect.

Infrared thermal imaging technology can directly and clearly locate manhole covers under asphalt pavement and can reduce the working hours required to locate manhole covers when pavement is being milled and repaved.

4. Analysis of Temperature Changes and Temperature Variation at Manhole Locations

We detected the temperature changes around a manhole cover using infrared thermal imaging technology and then used ANOVA to analyze the data statistically for each construction stage, as shown in Table 1. The univariate ANOVA F-test indicated there were significant differences between the temperatures before and after rolling compaction at locations around the manhole cover. The values of F and p were 661.47 and 6.06E-29, respectively. The rolling process was performed to ensure the required compaction of the asphalt concrete pavement, and the workability of the compaction is closely related to the temperature. Thus, the construction of manholes under pavement affects the overall temperature changes during rolling compaction. Because the temperatures are relatively low around manhole covers, cracks are commonly observed near them.

There are correlations between the temperature at locations with or locations without a manhole for open traffic both before and after rolling compaction. A significant difference was observed between the temperature in the presence or absence of the manhole cover before and after rolling compaction, and the p values were 2.43E-12 and 2.69E-17, respectively. In addition, the results revealed a significant difference in temperature between the presence or absence of a manhole cover for open traffic, with the p value being 6.90E-10 in this instance. The difference in these values implies that installing a manhole cover will influences the temperature uniformity of the pavement. Because of the significant differences in temperature at various pavement locations (with or without manholes), uneven loading from vehicles as well as lower pavement temperature around a manhole cover location, cracks commonly formed around the manhole location.

5. Effect of a Canvas Cover during Transportation of Asphalt Mixtures

In this study, a thermal imaging inspection system was used to assess the influence of a canvas cover on temperature changes in an asphalt mixture during transportation. Figs. 11 and 12 show thermal image temperature charts (temperature distribution at different points is plotted on the vertical axis, and temperature is plotted on the horizontal axis) for trucks carrying covered and uncovered conventional asphalt mixtures, respectively. The time required to transport the asphalt mixture from the mixing plant to the paving site was 30 minutes, and included highway travel for 20 minutes. During transportation, the temperature of the uncovered conventional asphalt mixture dropped to 24°C (on average), indicating that the absence of a canvas cover affected the asphalt mixture temperature. A comparison of Figs. 11 and 12 illustrates that the average surface temperature of the asphalt mixture with a canvas cover was approximately 24°C higher than without a canvas cover, thus confirming that canvas covers will reduce the rate of heat loss during transport.

Statistical analysis methods were used to analyze the central tendency and dispersion degree of temperature distributions to understand pavement temperature uniformity more clearly. Table 2 shows that the greater the standard deviation (σ), the more uneven the temperature distribution will be. The

Table 2. The effects of the presence or absence of canvas covers on conventional asphalt mixtures during transport.

Measurement Type	Avg. Temperature (°C)	Range of temperature change	Degrees of Freedom	SS	MS	Standard Deviation (σ)
Canvas cover	111.4	32.66	100	8974.508	89.745	9.473
No canvas cover	87.4	22.99	100	5300.967	53.010	7.281

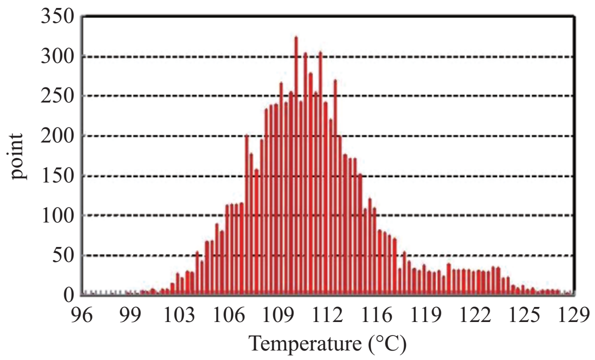

Fig. 11. Covered canvas temperature distribution chart.

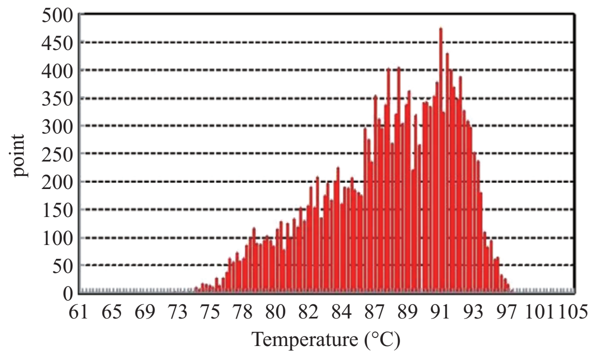

Fig. 12. Uncovered canvas temperature distribution chart.

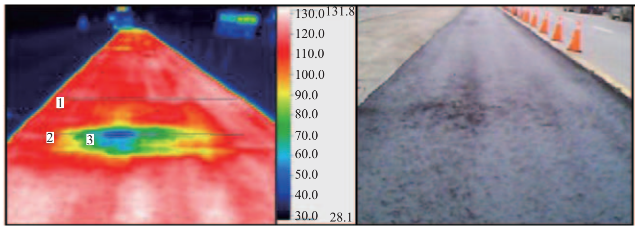

Fig. 13. Aggregate segregation seen in thermal-imaging analysis.

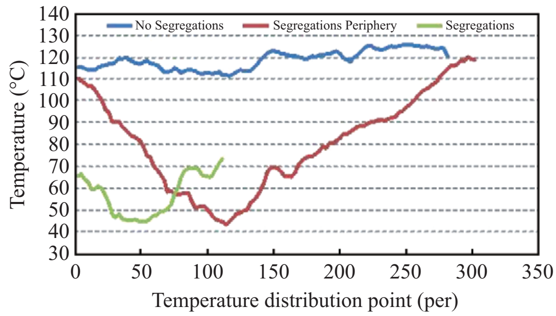

Fig. 14. The *in situ* temperature distribution of an asphalt mixture.

larger the indicated range, the greater the degree of dispersion or variation will be. As Table 2 illustrates, the range of temperature change for a conventional asphalt mixture without a canvas cover is smaller than a mixture transported with a canvas cover. In addition, conventional asphalt mixtures exhibited standard deviations of 9.473 and an average temperature of 111.4°C with a canvas cover and respectively 7.281 and 87.4°C without a canvas cover. Thus, conventional asphalt mixtures with a canvas cover will have high temperatures and also an uneven temperature distribution.

In contrast, the temperature distribution of the asphalt mixture without a canvas cover exhibited a low degree of dispersion. This comparison suggests that temperature uniformity closely relates to use of a cover. During the transportation process, rapid air currents come into contact with the asphalt mixture, causing heat loss from the mixture on the surface. A longer transportation time will affect cooling temperatures and cause the surface temperature to be closer to the actual air temperature. Even when the asphalt was covered, the canvas had holes of different sizes, which also resulted in complex heat loss behavior and uneven temperature conditions.

6. Aggregate Segregation

After a transporter pours an asphalt mixture into a paver hopper, residual asphalt mixture can remain in the hopper. Paver drivers may dump that leftover mixture on unpaved road sections. Because the dumped mixture has already cooled, it is difficult to mix it uniformly with any fresh asphalt mixture poured by a paver onto the paving section. This problem results in aggregate segregation.

Fig. 13 depicts a thermal image and an in situ photograph taken after initial rolling compaction. Clearly, the temperature in the area surrounded by aggregate segregation was reduced and affected by that aggregate segregation. Fig. 14 illustrates the in situ temperature distribution of asphalt mixtures (temperature distribution at different points is plotted on the horizontal axis), categorized into three sections, namely, no segregation, segregation periphery, and segregation. In the nonsegregation section, the temperature approaches the initial rolling compaction standard temperature of 120°C. In the aggregate segregation periphery section, because the temperature is affected by the dumped mixture, the temperature

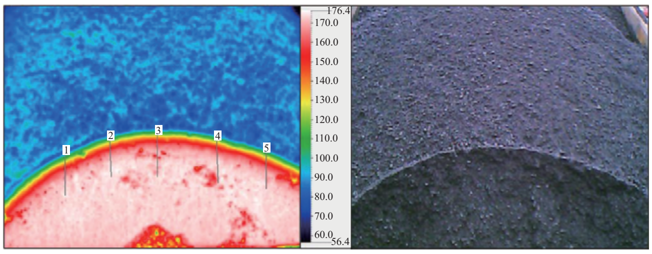

Fig. 15. Surface and interior temperatures in the transporter.

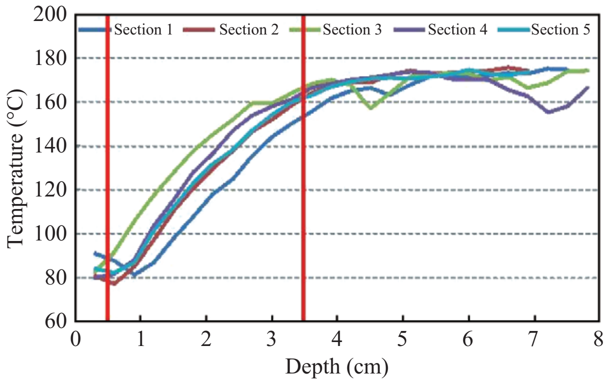

Fig. 16. Changes in surface and interior temperature in the transporter.

decreases very significantly. In the aggregate segregation section, the temperature decreases to 45°C after the initial rolling compaction. Hence, the quality of compaction becomes difficult to control at this low temperature. This lack of quality control can lead to durability concerns for the pavement in the future.

7. Asphalt Mixture Quality in the Transporter

Asphalt mixtures segregate mainly due to the presence of a localized large amount of fine or coarse aggregates and an uneven distribution of aggregates and asphalt. Aggregate segregation predisposes a road to early damage. Fig. 15 illustrates the difference in temperatures between the surface and the interior, determined by infrared thermal imagery, of an asphalt mixture in a transporter. In general, the temperature of the asphalt mixture was between 155 and 170°C at the milling plant. As Fig. 16 shows, the temperature of the asphalt mixture was measured in five sections to avoid sampling bias. The horizontal axis indicates temperature changes in the asphalt mixture based on depth, and the vertical axis indicates the temperature in the five sections. The surface temperature distribution was 81 ± 6°C. Compared with the temperature of the asphalt mixture at the milling plant (155 to 170°C), the surface temperature of the asphalt mixture dropped to 81 ± 6°C because the surface area came in contact with air, which cooled the mixture during transportation. Yet, the temperature remained high in the deep layers of the asphalt mixture.

Infrared thermometers are often used for in situ quality control based on temperature variation; however, as a single point can be examined at one time, uniformity across the entire paving area can still be lacking. Nonetheless, using infrared thermal imagery to detect temperature distribution uniformity during paving does enable better analysis of overall construction quality.

IV. CONCLUSION

1. It is difficult to directly obtain the overall temperature distribution of a pavement by conventional infrared temperature-sensing guns which can detect the temperature only in a pointwise manner. The infrared thermal imaging technology, however, is expected to directly evaluate the uniformity of temperature distributions and will help elucidate the relationship between the uniformity and compaction of asphalt pavements, thereby to ensure the quality of rolling compaction and prolong pavement's lifetime.
2. When constructing asphalt concrete pavement, a manhole cover did not affect the temperature before rolling compaction, as the main reason is that the aggregates were in a loose state. However, after rolling compaction, the contact area between the manhole cover and the pavement increases, the pores of the aggregates decrease in size, and heat transfer is thereby enhanced. Therefore, the temperature of the pavement above the manhole cover significantly decreases, resulting in inadequate compaction. Thus, cracks and signs of damage easily appear near the manhole cover on asphalt concrete pavements with open traffic.
3. The temperature of the pavement around the outer edge of a manhole cover is lower than the temperature over the center of the manhole cover. In addition, the temperature of the asphalt concrete pavement close to the manhole is higher than that at the manhole location. This difference in findings could be caused by the thermal conductivity difference between the iron material of the manhole cover and that for the asphalt concrete because iron absorbs heat.
4. When a manhole cover is located beneath asphalt concrete pavement, because the rolling temperature is inadequate and the temperature distribution is uneven around the manhole cover, it can be difficult to control the quality of the pavement during the paving process. Consequently, the asphalt concrete around the manhole location is susceptible to damage.
5. Infrared thermal imaging technology can be used to determine the location of manhole covers more quickly and accurately, thereby reducing work hours and future/ongoing damage to pavements.

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