Applications of Thermography in Pavement Engineering

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ABSTRACT

Thermal imaging has been used in pavement engineering for quality control of asphalt paving operations, during initial application for the most part. This paper however, focuses on evaluation of existing pavements, their performance and maintenance, specifically looking at two case studies. In the first study, the diurnal temperature cycle and temperature differences between different lanes of a highway are investigated. The most probable reasons for these differences are the exposure to direct sunlight (the slow lane receiving much less direct sunlight than the fast lane where less traffic is present) and the different materials used in the layer construction. The information obtained from this investigation can assist in the correct maintenance of the asphalt, as asphalt is temperature sensitive during use, and a pavement operating at a higher than optimal temperature may be potentially more prone to rutting. The second case study focuses on the temperature variances of tires used at different operational conditions. Research has shown that over-inflated or overloaded tires have higher tire-pavement contact stresses in the centre of the tread, while tires operating at overloaded and under-inflated conditions have higher contact stresses on the sidewall areas of the tread. The data collected can assist in determining the causes and solutions to excessive fatigue and rutting in pavement surfaces. In conclusion, this paper demonstrates the potential benefits of using infrared (IR) thermography as a tool for the evaluation, and predictability, of pavement performance.

INTRODUCTION

Thermal imaging has been used in pavement engineering for quality control of asphalt paving operations. Due to the sensitivity of asphalt to temperature variations during placement and compaction, this application has been widely researched and applied. Mahoney et al (2000) and Myers et al (2001) investigated the effects of segregation in asphalt mixtures on the surface temperatures of the asphalt, as well as the final compaction and expected performance of these pavements. Oloufa et al (2004) investigated crack detection in asphalt pavements using thermography.

However, a large portion of pavement engineering focuses on the evaluation of existing pavements, their performance and maintenance. It would thus make sense to investigate applications of thermography in pavement performance and maintenance actions. This paper focuses on some of these potential uses, looking at two specific case studies.

In the first study, the effects of diurnal temperature changes as well as differences in pavement materials on the operational temperature surface of the pavement are investigated, and the potential effects of these changes on the pavement performance discussed. Diurnal temperature variations affect the pavement temperature, although not uniformly for all materials. This is shown for a pavement where the base layer materials differ from each other and where the resultant diurnal surface temperature varies between the different portions of the pavement. The potential of thermal imaging to assist in detecting the presence of different materials in the layer below the surfacing of the road (base layer) through surfacing temperature variations is shown. This case study follows evaluations performed on two roads where the base layer material varied between natural gravels and gravels with added bitumens. The effect of base materials on surface temperatures is also correlated in the laboratory.

In the second case study, the surface temperatures of truck tires is evaluated to determine the impact their inflation pressures has on road surfacing. Earlier research on these contact stresses has indicated that specific patterns can be observed for under-inflated and over-inflated tire conditions. Evaluation of the sidewall and tread temperatures of operational truck tires can assist in this procedure.

First, this paper will provide a short introduction into temperature measurements in pavements and tires. Next, information is provided on the specific infrared camera used to take the measurements and the two modes of operation used in the case studies. The focus then moves to the two specific case studies with a final section focusing on the potential practical applications of these features.

PAVEMENTS BACKGROUND

A pavement typically consists of various layers of material to provide a structure that can carry the applied traffic loads with a certain degree of serviceability. The two important layers for the purposes of this paper are the surfacing (mostly asphalt) and the base layer just below the surfacing (consisting of bituminous stabilized, cement stabilized or natural gravel materials). Road pavements undergo a diurnal cycle of temperatures, as well as an annual seasonal cycle of temperatures, mainly through their direct exposure to sunlight. Asphalt, which essentially consists of aggregate and bitumen, is a temperature-susceptible material which behaves differently at various temperatures. The most noticeable effect of temperature on asphalt is the potential for cracking at low temperatures and the potential for rutting at high temperatures. Granular and cemented pavement materials are less prone to temperature-related effects.

TIRES BACKGROUND

Vehicle tires serve four basic functions on a vehicle (Gillespie, 1992) - they support the vertical wheel load; develop longitudinal forces for acceleration and braking; enable directional change of the vehicle, and develop braking forces. When a tire rolls on a pavement, several loads and stresses are imparted onto the tire, causing the tire to flex. This flexing causes heat build-up in the tire. The amount of flexing (and thus heat build-up) is affected by factors such as the tire load, inflation pressure and construction.

Research by De Beer et al (2004) focused on the contact stresses that develop between the tire and pavement surface. These contact stresses are affected by the operational wheel load and tire inflation pressure. Typically, an n-shape contact stress pattern will develop for overloaded, over-inflated tires (Figure 1 - left), while an m-shape contact stress pattern will develop for under-inflated tires (Figure 1 - right). These shapes are measured using a SIM system (De Beer et al, 2004) which is relatively expensive and complicated to operate. The contact stress patterns applied to a pavement have a direct influence on the damage imparted to the pavement (especially the surfacing layer). Thus, it is important to road owners to monitor wheel loads (typically through weigh bridges) and tire inflation pressures. The latter is not a trivial exercise on highways.

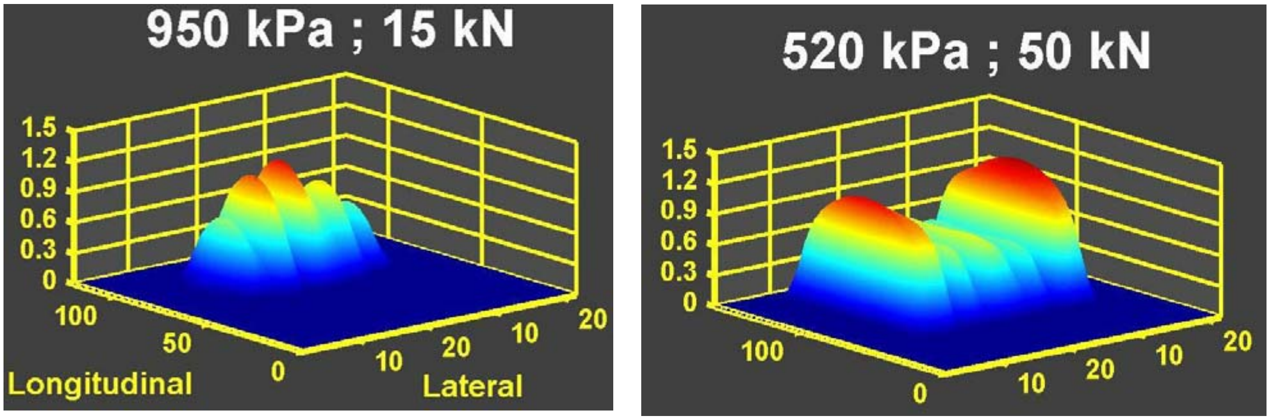

Figure 1. Typical tire-pavement contact stress: Left – over-inflated tire; Right – under-inflated tire.

INSTRUMENT AND METHODS USED

The thermal imaging for this study was performed using a Raytek Ti30 device. It operates in the 8 to 14 µm wavelengths and has a resolution of 160 by 120 pixels. As all the pavement surfacings were of similar asphaltic properties the emissivity of the device was set at 1.00 for all measurements. Oloufa et al (2004) found that thermography in the Far Infrared (or Long Infrared) wavelengths (7 to 14 µm) provides better images of typical asphaltic surfaces heated by the sun.

Thermography can be performed using two different methods for the type of work discussed in this paper. These are either as a device to identify and locate temperature differences between various objects in an image, or as a collector of large quantities of temperature data of a specific sample. The first method is often used when the objective of the survey is to identify areas in asphalt surfacings where segregation of the asphalt occurred, densities are dissimilar or cracks developed (Mahoney et al, 2000; Myers et al, 2001). However, the second method was used for the case studies in this paper. The objective of each of the studies was to obtain a large sample of temperature data (approximately 10,000 data points per sample) from different targets to enable a statistically sound comparison to be made. For these case studies, the anticipated condition of each of the targets was known, and therefore the focus was not on identification of temperature differences within a specific thermogram.

CASE STUDY 1: PAVEMENT SURFACE TEMPERATURES

In the first case study, the diurnal temperature cycle and temperature differences between different lanes of a highway are investigated. In Figure 2 a portion of highway is shown where the slow lane is operating at a higher temperature than the middle and fast lanes. This phenomenon is most pronounced during the afternoons (Figure 4). The main difference between these lanes is that the fast lane has less than half the thickness of bituminous material over the base layer than the slow lane. All the lanes have exactly the same surfacing and thus the color of the surfacing is similar. In Figure 3 the surface temperatures of three different sections of road are shown. These sections again had similar surfacings, but one base layer was stabilized with bitumen, one with cement and one was not stabilized at all. The sections stabilized with bitumen showed the highest surface temperatures with the unstabilized sections showing the lowest surface temperatures.

In order to investigate this phenomenon further, two cores collected from the road were heated in the sun and allowed to cool back to ambient temperature while the temperatures were measured at various intervals. The results of this investigation indicated that, although the two cores started at the same surface temperature, the bitumen stabilized core increased to a slightly higher temperature while in the sun, and this temperature difference remained, even after 5 hours of cooling. It thus appears as if the effect of the bitumen in the base layers can cause the surface temperature of the pavement to differ, as observed in Figure 3.

The effect of diurnal temperature cycles on the pavement surfacing was also investigated. Thermograms of similar pavement sections were taken just after sunrise, and early afternoon. The results of these measurements are shown in Figure 4, indicating that the time of day and subsequent ambient temperature and position of the pavement in its diurnal cycle also affects the data obtained. The temperatures of the slow and fast lanes (shown in the figure) are similar early in the morning (left of Figure 5) while the afternoon data (right of Figure 5) shows a difference (warmer slow lane than fast lane) in the temperatures. These differences are probably due to the movement of the heat through the pavement during the day, causing the different base layer (and thinner bituminous layer) of the fast lane to affect the surface temperature, while the cooling period during the night causes the two lanes to show similar temperatures in the morning.

Potential applications for the case study

The information obtained from this investigation can assist in the correct maintenance of road asphalt, as asphalts are temperature sensitive during use, and a pavement operating at a higher than optimal temperature may be potentially more prone to rutting. The data collected can also assist in the process of identifying areas where the base layer of the pavement (that is not visible to the eye as the surfacing would be) varies from the rest of the pavement structure. There may be areas where inadequate stabilization occurred or even areas where changes in in situ moisture content may cause differences in performance of the pavement.

Essentially, the information assists the pavement engineer to identify areas of non-homogeneity in the pavement, even when the surface appears to indicate a homogeneous pavement structure.

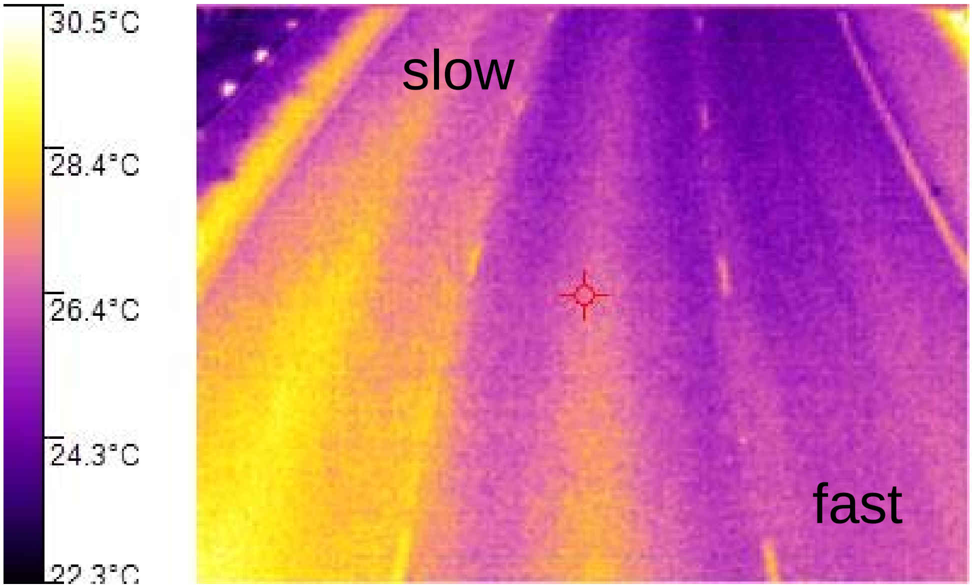

Figure 2. Typical thermogram of a highway showing different surface temperatures for different lanes.

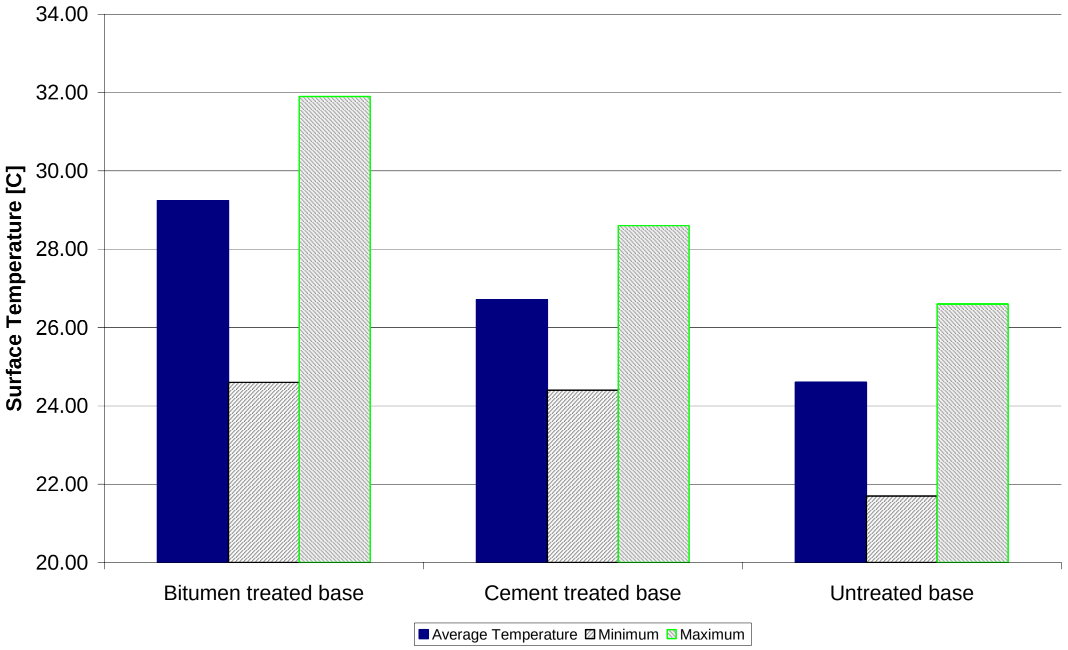

Figure 3. Surface temperatures of 3 different pavements indicating effect of different base materials on surface temperature.

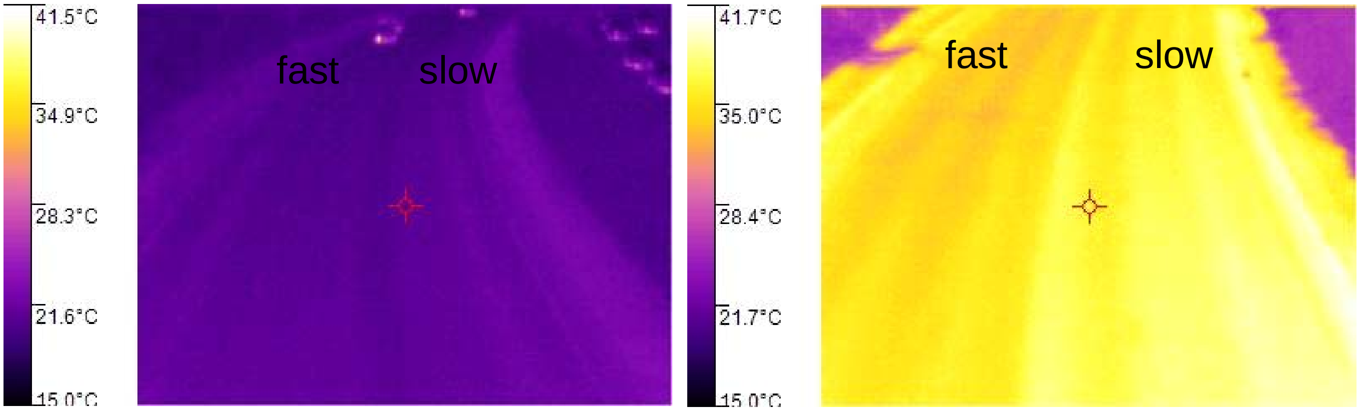

Figure 4. Diurnal temperature effects on pavement surfaces: Left – morning, Right – afternoon - (similar temperature scale).

CASE STUDY 2: TIRE TEMPERATURES AND OPERATING CONDITIONS

The second case study focuses on the temperature variances of tires used at different operational conditions. Research has shown that over-inflated tires have higher tire-pavement contact stresses in the centre of the tread, while tires operating at under-inflated conditions have higher contact stresses on the sidewall areas of the tread (Figure 1). Following this, the temperatures of tires being operated at various operational conditions were measured, and it was shown that the temperature regions on the tires followed a similar pattern. This information can potentially assist in the identification of overloaded over-inflated conditions in tires, a condition with the potential to cause excessive fatigue and rutting in pavement surfacings.

Analysis of the contact stress patterns developed during over-inflated and under-inflated operation of tires leads to the hypothesis that the surface temperatures of the tread and sidewalls of the two conditions should be indicative of the contact stress pattern. This hypothesis was first evaluated by monitoring truck tires on the road. In Figure 5 two typical conditions observed are shown. On the left a tire with a hotter tread is shown while the tires on the right are showing hotter sidewalls.

In order to evaluate the phenomenon under controlled conditions, the tires on a Heavy Vehicle Simulator (HVS) were firstly over-inflated and allowed to run under a certain load until the tire temperatures stabilized, and then the same exercise was repeated with under-inflated tires. The tire tread and sidewall temperatures were monitored during the test. In Figure 5 typical temperatures for a tire tread (left) and sidewall (right) as monitored on the road are shown, while Figure 6 shows the typical tread and sidewall tire temperatures measured during the experiment on the HVS. In Figure 7 the analyzed temperatures are shown as the increase from the starting (cold) temperature to the stable temperature. Analysis of the data in Figure 7 indicates that, while both sidewall and tread temperatures increased under over-inflated conditions by a similar margin, the sidewall temperature increased substantially more under under-inflated conditions than the tread temperature. This correlates broadly with the tire-pavement contact stress patterns shown in Figure 1, indicating higher contact stresses in under-inflated conditions than in normal or over-inflated conditions.

Potential applications for the case study

The information provided in this case study can potentially be used to monitor truck tire conditions at locations such as weighbridges. It is not currently possible to monitor tire inflation pressures on a routine basis for moving vehicles. However, through monitoring of the tire temperatures (and specifically the sidewall and tread area temperatures) it should be possible to identify those tires on a moving vehicle where either the tread or the sidewalls are operating at an elevated temperature. These conditions may trigger attention of an operator who can then stop a vehicle and physically verify tire inflation pressures.

This procedure will have a dual purpose. It should alleviate very high tire-pavement contact stresses through ensuring more uniform tire-pavement contact stress conditions, and it may also assist in truck safety, as potential blow-outs of tires due to under-inflated operation may be alleviated.

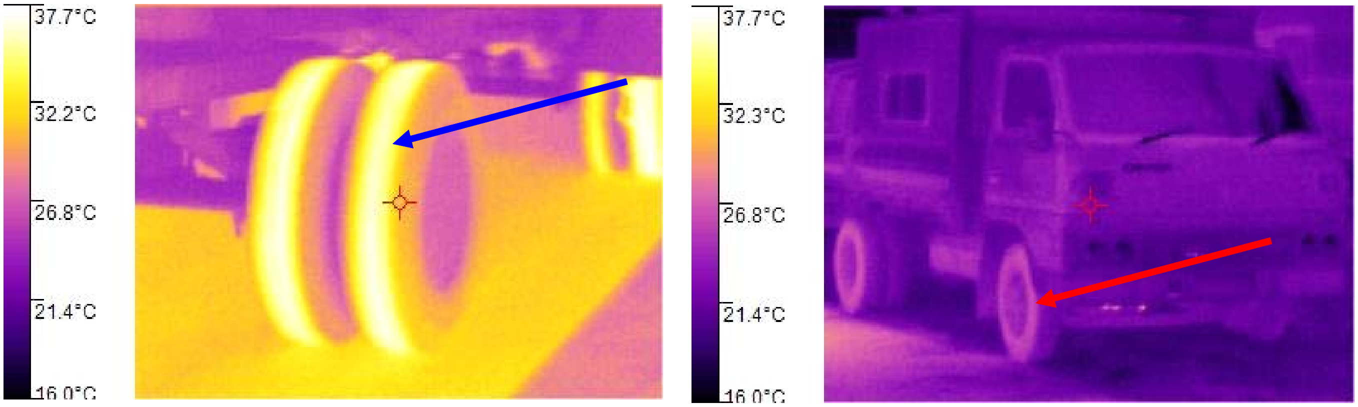

Figure 5. Typical truck tire temperatures as observed on the road: Left – hotter tread; Right – hotter sidewall – (similar temperature scales).

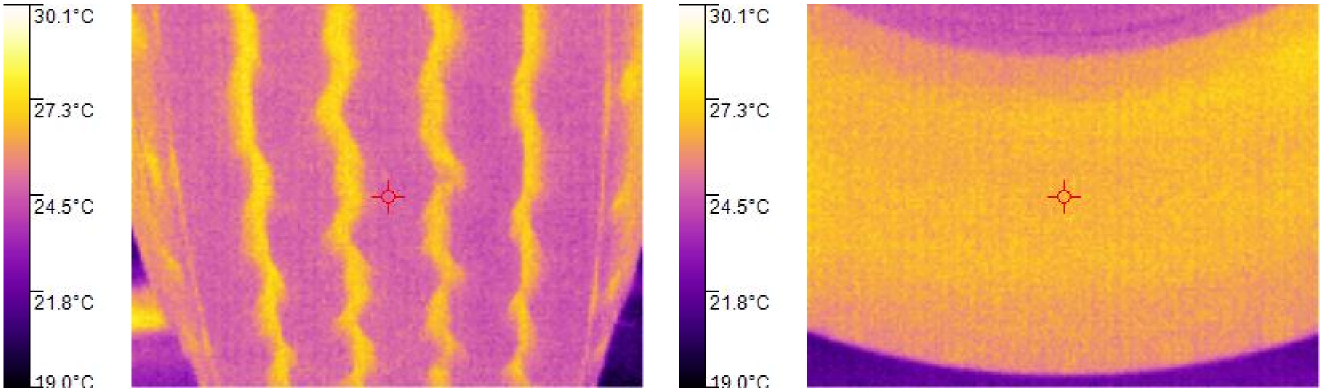

Figure 6. Typical HVS tire temperatures for tread (left) and sidewall (right) - (similar temperature scale).

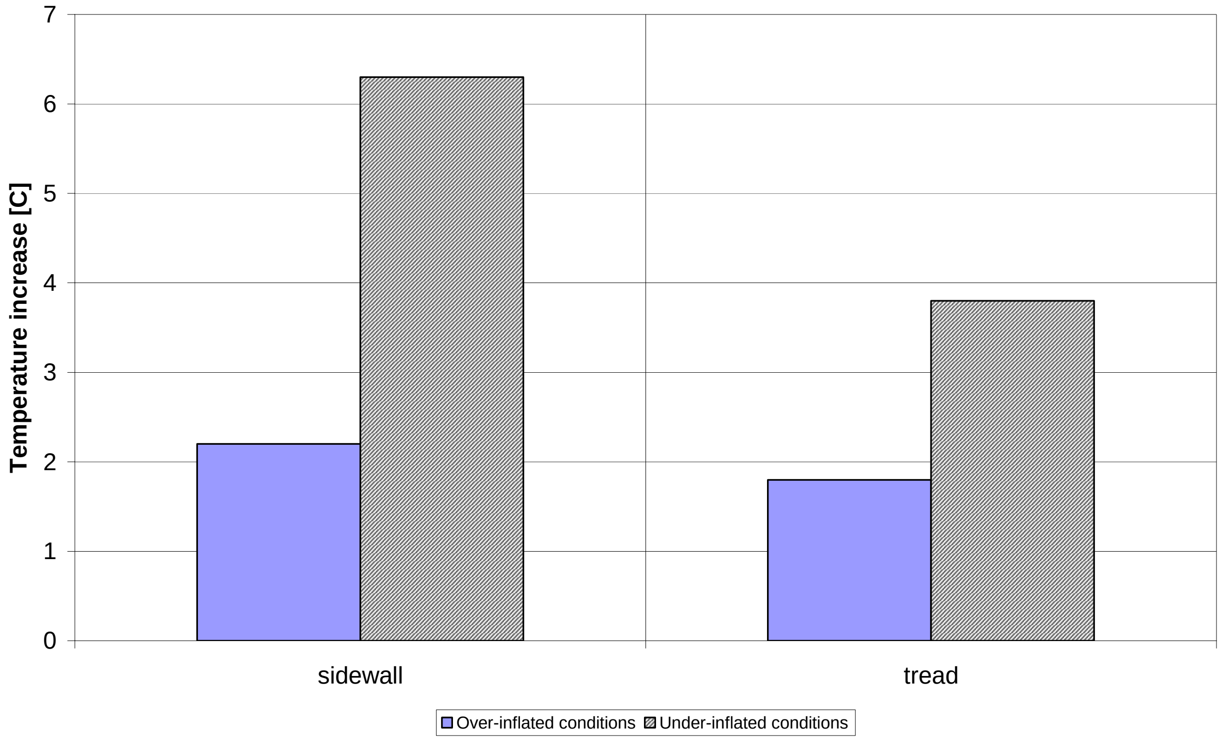

Figure 7. Increases in tire tread and sidewall temperatures under over-inflated and under-inflated conditions.

POTENTIAL BENEFIT TO PRACTICE, APPLICATIONS AND FURTHER WORK

Thermography

The question may be asked as to why infrared is required to obtain the information presented and discussed in this paper - most of the data could also be obtained through more traditional measures such as thermocouples at a much reduced cost for the equipment. However, for these types of investigations it is important to obtain a large sample of data to ensure that local hot or cold spots are not influencing the analysis. To this end, thermography provides a method to quickly collect a large data sample from which a statistically significant deduction can be made, with the potential for errors taken into account.

Further, the option of identifying localized areas of non-homogeneity in pavement structure remains a strong reason for utilizing infrared equipment. Often (as shown in the discussion on the effects of base layer material on surface temperatures) the non-homogeneous nature of the pavement may not be visible to the eye on the surface of the pavement – at least not before deterioration starts at the location. Thermal imaging provides the means to identify these conditions before they lead to undue deterioration and failures.

Other potential applications

The information on the effects of different stabilizers on the surface temperature of road building material leads to the logical use of thermal imaging in the laboratory, where various experiments are being conducted using road building materials stabilized with bituminous, cementitious and other stabilizers. Each of these stabilizers has a different reaction with the virgin material, and it is crucial to determine the period required for curing of the stabilized material before any engineering tests are conducted on the sample. The use of thermography for the evaluation of these curing times may be investigated. In a preliminary study, two gravel samples were monitored in the laboratory using infrared. The one sample was a neat gravel, while the second had 3 per cent cement added as a stabilizing agent. The temperatures (average of approximately 10,000 data points) obtained from the IR thermograms are shown in Figure 8.

The effect of the cement stabilizer is clear in the average surface temperatures of the two samples. After a period of almost 19 hours, the temperatures of the two samples were similar, possibly indicating that the curing process in the stabilized sample has been completed. Much more work is required in this area, but these initial results may indicate a promising use of thermography as a quality control instrument in the pavement materials laboratory.

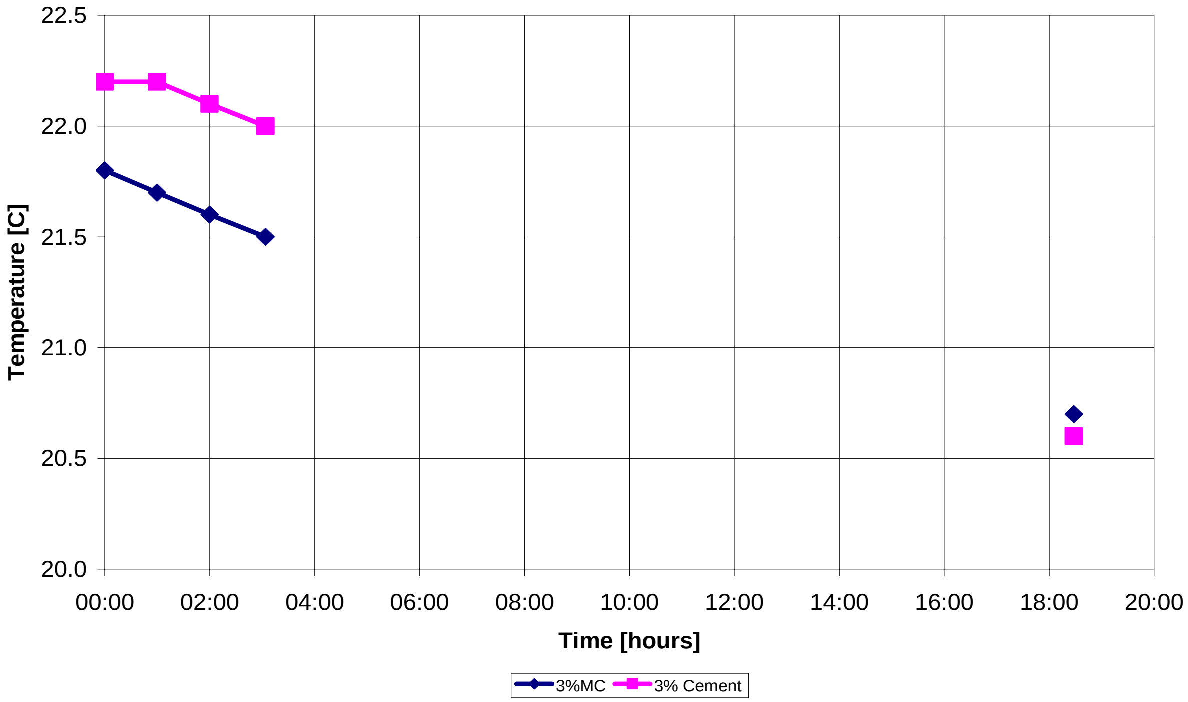

Figure 8. Typical effect of stabilizing agent on surface temperature of laboratory sample of road building material.

SUMMARY

In this paper, the effects of temperature on pavement and tires were investigated using thermal imaging. The objective of the paper was to demonstrate some of the potential applications of infrared in pavement engineering and vehicle-pavement interaction on a day-to-day basis.

General

The benefit of thermography for use in pavement engineering and vehicle-pavement interaction fields is mainly in the large sample of temperature measurements that can simultaneously be collected, enabling a statistical analysis of the temperature data.

Pavement surfaces

Pavement surfacings often do not show any initial indication of potential failures due to the support from lower layers in the pavement, or to differences in the consistency of the surfacing material. Through the use of thermography, a rapid assessment can be made of the pavement to identify any non-homogeneity in the pavement surface temperature. Provisional investigations have shown such non-homogeneous surface temperatures to be indicators of possible surfacing matrix variances or base layer variances which may lead to materials failure.

Tires

Non-uniform contact stresses applied by tires to pavement surfaces can be detrimental to the performance of the surfacing. Temperature differences between the sidewall and tread of the operational tire, or excessive tire temperatures have been shown to be indicative of operational conditions that may cause such non-uniform contact stresses. The potential application of infrared thermography at weighbridges as a sensor for identifying inappropriate tire operational conditions has been identified.

Other potential applications

Preliminary investigations have shown that IR thermographic applications in the pavement materials laboratory, where issues such as determining curing requirements of stabilized materials may be assisted through evaluation of the temperature profiles of material samples. Although this work is still in its infancy, further investigation, also focusing on stabilizing with bituminous products, is ongoing.

In general, the availability of thermal cameras at affordable price points may well lead to this technology becoming the benchmark in the pavement materials and engineering field as a standard tool.

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ACKNOWLEDGEMENTS

The author wishes to thank the Director of CSIR BETEK for providing the resources to make this work possible.