A Methodology for Real-Time 3D Visualization of Asphalt Thermal Behaviour During Road Construction

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D. S. Makarov, F. Vahdatikhaki, S. R. Miller, and A. G. Dorée

Abstract

Asphalt mixture temperature plays an essential role in the road construction process. For high-quality asphalt, it is crucial that the compaction is performed within a certain range of the temperature, known as the compaction window. The compaction of the asphalt at a temperature outside this range would compromise the quality of the final product considerably. The compaction window is predicated on a myriad of parameters such as the type of the asphalt mix, the ambient temperature, etc. However, the operators of the road construction equipment (e.g., rollers and pavers) currently rely on their professional intuitions and experiences to develop their operational strategies. This practice can be significantly improved if the operators can be provided with the real-time information about the temperature of the asphalt mat during the construction. The available solutions for the real-time monitoring of the asphalt are limited to capturing and presenting only the surface temperature or only core temperature of the asphalt mat. Given the complex behaviour of the asphalt with relation to the mixture type and the ambient conditions, this approach cannot best represent the asphalt behaviour during the construction. This paper presents an approach for capturing the real-time asphalt behaviour using multiple sensing technologies. In this approach, the core and surface temperatures of the asphalt are captured using thermologger and linescanner, respectively. These data are then translated into 3D temperature contour plots that represent the asphalt behaviour under the construction site settings in real time. Finally, the data is presented to the equipment operator via a user interface. A prototype is developed and tested to demonstrate the feasibility of the proposed approach. The case study indicates that the presented method can improve the asphalt operation by enabling the operators to better develop their operational strategies.

Keywords

Asphalt construction • Real-time condition assessment • Sensors • Operator guidance system • 3D visualization

96.1 Introduction

Roads play an essential role in the modern society, providing economic growth and facilitating communication and transportation between cities, regions, and countries. Because of this and given the growing size of the road networks in the world, it is becoming ever more important to improve the road quality to reduce the cost and disruptions caused by road maintenance work. In many countries, Hot Mixed Asphalt (HMA) is the preferred and dominant material for road construction. However, HMA is very sensitive to the construction process and it is vital to ensure that the construction process results in a quality comparable to the standards set during the design of HMA.

Conventionally, the asphalt density is perceived as the prime indicator of the quality of HMA work [1, 2]. There are sensor-based solutions that can measure the asphalt density during or after the construction [3–5]. However, research shows that the compaction needs to happen within an appropriate temperature range to ensure a high-quality HMA [6, 7]. This range

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is usually determined during the laboratory testing. The compaction force applied to the asphalt above or below an ideal temperature range would result in an over-stressed or an under-stressed condition, respectively [8]. Traditionally, operators of the road construction equipment would use their intuition and rules of thumb to determine when, where and how much to compact. This approach has been shown to be suboptimal [9]. The compaction practice can be significantly improved if the operators are provided with the real-time information about the temperature of the asphalt mat during the construction [8].

There are several solutions that are designed to provide the operators with real-time temperature data. The available solutions can be categorized into two major classes: (1) the behaviour of the HMA is approximated by theoretical models. In many instances, these theoretical models fail to account for construction conditions and, thus, can be inaccurate. Additionally, these solutions require a great deal of input data from users (e.g., paving and compaction period and time, environmental conditions, existing surface conditions, and mix specifications). The need for a considerable number of user inputs negatively impacts the system usability and practicality. (2) The HMA behaviour is modeled based on the real-time data collected from the site [10–12]. Since this class of solutions rely on actual data collected from the site, they tend to be more accurate and reliable. Nonetheless, the available data-driven solutions focus only on either the core or surface temperature of the asphalt. This can be misleading because depending on the weather condition and the type of the mixture, there can be a large temperature gradient between the core and surface of the asphalt. Additionally, there is an assumption that mixture delivered on the site has a uniform temperature gradient because it is remixed in the paver. This notion has been shown to be fallacious [9, 13]. The other expectations are that the core temperature of the asphalt mat is ‘hotter’ and more uniform in comparison with the surface temperature. This neglects the heat transfer and thermal conductivity that show the differences in temperature gradient. In these situations, the single temperature approach (be it that of core or surface) can lead the operators to adopt over-conservative (e.g. the asphalt mixture might be under compacted) or over-aggressive (e.g. the asphalt mixture might be over compacted) compaction strategies. Therefore, it is important to represent the temperature information in such a manner that the operators are well-informed about the gradient between the core and surface of the asphalt.

Motivated by the above-mentioned gaps in the research, this paper presents a comprehensive methodology for (1) developing a real-time system that integrates data from various sensors to automatically generate the real-time temperature contour plots of the asphalt considering both the core and surface temperatures, and (2) visualizing the asphalt temperature data in a 3D format that can help operators develop effective compaction strategies.

96.2 Real-Time Asphalt Temperature Monitoring and Prediction

96.2.1 Principles of 3D Temperature Contour Plots

There are several theoretical models that can be used to predict the asphalt temperature based on heat transfer law and thermal conductivity [14, 15]. However, given the complexity of the parameters that affect the behavior of the HMA, in this paper the focus is placed on the estimation of the temperature based on real-time measurement.

The temperature profile of the paved asphalt layer can be represented in 3D manner based on corresponding temperature values collected from layer’s surface and core. This profile, namely a 3D temperature contour plot, can provide more insights into the temperature homogeneity of asphalt mixture, and real-time asphalt mixture thermal behaviour. Currently, the setup of sensors to measure temperature values at different locations of the paved section, can interfere with main asphalt team activities. To prevent possible interventions of asphalt construction, and to reduce the chance of collisions with construction machines on site, the non-intrusive strategy of site data collection is developed. The principles of temperature data collection for the generation of 3D temperature contour plot is shown in Fig. 96.1. As shown in this figure, at least four different types of temperature data need to be determined.

1. Reference Surface Temperature (RST): the surface temperature at a predefined and fixed reference point which is set up at the start of the project;
2. Reference Core Temperature (RCT): the core temperature at the reference point;
3. Target Surface Temperature (TST): the surface temperature of any other given points on the asphalt mat;
4. Target Core Temperature (TCT): the core temperature of any given points on the asphalt mat.

In the developed method, a reference point is a location on a construction site where RSTs and RCTs of the paved asphalt are collected continuously in real-time. The TST at the beginning of the asphalt construction is measured when the paver lays the asphalt mat. The following TST values are calculated based on Eqs. 96.1 and 96.2.

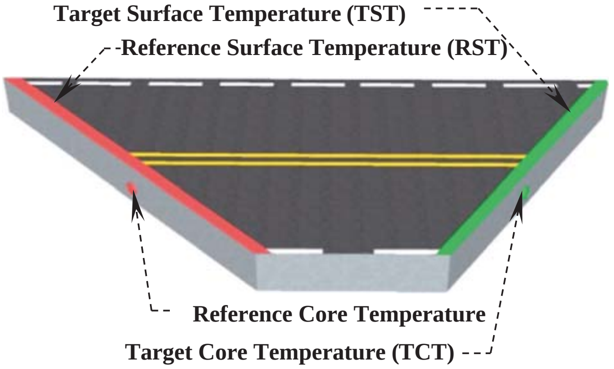


Fig. 96.1 Schematic representation of the data required for generating the 3D contour plot

$$\Delta RST_t = RST_t - RST_{t-1} \tag{96.1}$$

$$TST_{t,j} = TST_{t-1,j} + \Delta RST_t \tag{96.2}$$

where:

t	is an index representing the time step of the data collection,
j	is an index representing the location of the target point,
$\mathbf{\Delta RST_t}$	is the temperature gradient of the surface at the reference point at time t,
$\mathbf{TST_t}$	is the target surface temperature at time t.

Assuming that the thermal behavior of the asphalt mat is homogenous, the core temperatures of the paved asphalt section (TCTs) can be calculated based on TSTs at any given time (Eqs. 96.3 and 96.4).

$$\Delta RT_t = RCT_t - RST_t \tag{96.3}$$

$$TCT_{t,j} = TST_{t,j} + \Delta RT_t. \tag{96.4}$$

where:

$\mathbf{\Delta RT_t}$	is the temperature gradient between core and surface at the reference point at time t,
$\mathbf{TCT_t}$	is the target core temperature at time t.

Based on TST and TCT values of different parts of the road, the 3D temperature contour plot can be created. To capture the differences between surface and core temperature values and to be able to represent them on the edges of 3D plot the interpolation method is used (Eq. 96.5).

$$\left[\begin{array}{ll} T_x = \left(\frac{T_{S2}-T_{S1}}{L_1}\right) \times x, & S2 < x < S1 \\ T_x = \left(\frac{T_{S3}-T_{S2}}{L_2}\right) \times x, & S3 < x < S2 \end{array}\right. \tag{96.5}$$

where:

$\mathbf{T_x}$	is the core temperature of an asphalt layer at the depth x,
$\mathbf{T_{s1}}$, $\mathbf{T_{s2}}$, $\mathbf{T_{s3}}$	are surface and core temperatures of an asphalt, measured by sensors at surface point S1, and in depth S2, S3,
$\mathbf{L_1}$, $\mathbf{L_2}$	the corresponding differences between depths S2 and S1, S3 and S2,
x	every depth along the thickness of the asphalt layer.

96.2.2 The Architecture of the Proposed System

The proposed real-time system intends to collect, analyze and merge two sources of data: (1) capture reference temperatures (RST, RCT) of the asphalt, and (2) generate a reliable representation of current temperature of the asphalt at different part of the mat (TST and TCT), using the principles explained in Sect. 96.2.1. For this purpose, two stations are developed, namely, the Reference Station and the Paver Station (Fig. 96.2).

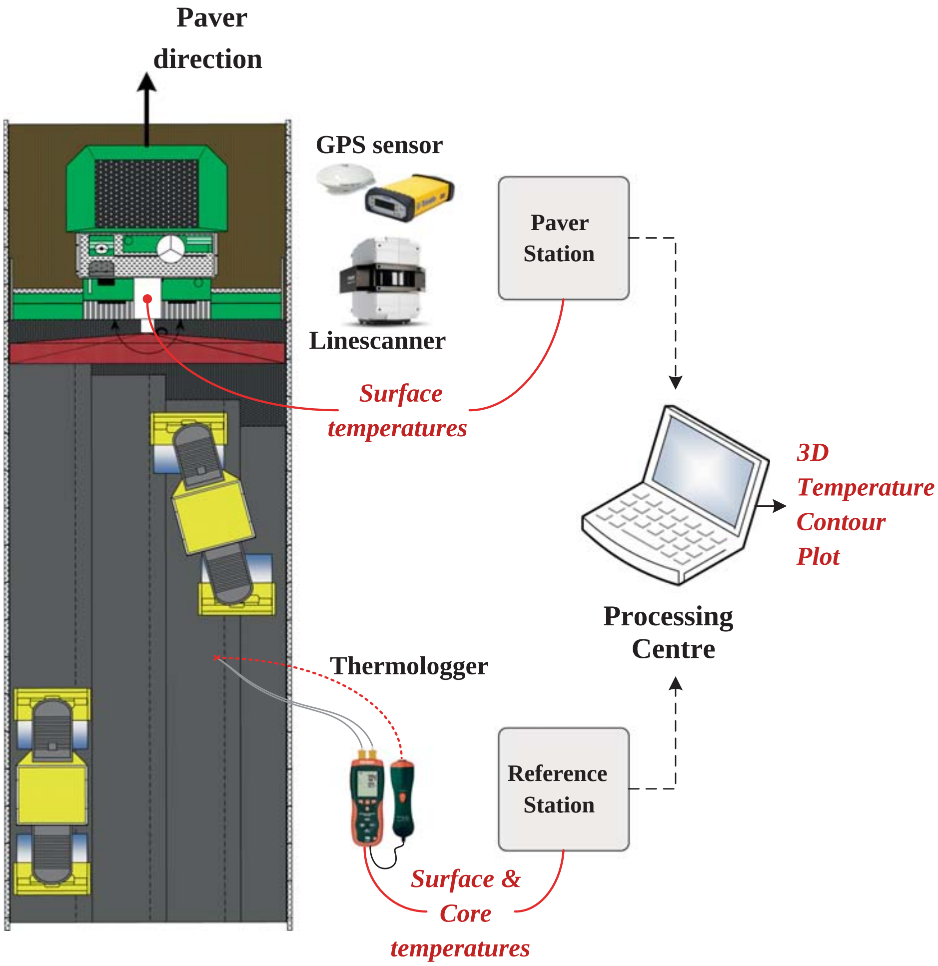
The Reference Station is responsible to continuously measure the temperature of the asphalt at the core and on the surface of the asphalt and determine the corresponding temperature differences. The Paver Station, on the other hand, intends to measure the surface temperature of the asphalt behind the screed of paver and register this data. These two stations send their data to the Processing Centre, where the asphalt temperature gradient at the reference point is projected onto the surface temperature of the asphalt at different parts of the mat. Further the 3D temperature contour plots of the asphalt are created. The remainder of this section explains each one of these components in detail.

96.2.3 Reference Station

During the paving of any given segment, the temperature data from the relevant reference point is used. The data flow from the reference point should be continuous until the lower threshold of the compaction window is reached. To fit with a non-intrusive requirement, the thermologger which can read and transfer data from thermocouples and infrared channel, is used at the Reference Station.

The thermocouples are implemented into the asphalt layer just after the paver laid the corresponding section of the road. The depths at which thermocouples are placed should differ to get better representation of temperature profile of the asphalt

Fig. 96.2 Overview of the proposed system



section. The data set of surface and core temperatures at a reference point is processed on site and result are transferred to the Processing Centre for further analysis. Figure 96.3a shows the structure of the Reference Station. The Reference Station uses a router to transmit all the data to the Processing Centre, where these data are integrated with the data from Paver Station to generate the 3D temperature contour plots.

96.2.4 Paver Station

As explained in Sect. 96.2.1, it is assumed that the data gathered from the Reference Station represent the behaviour of the entire asphalt segment. However, to generate the 3D temperature contour plots based on the Eqs. 96.1–96.4, the surface temperatures of the asphalt at different parts of the mat need to be collected. This can be done by the temperature sensor that is mounted on a paver before the construction project starts. Like the Reference Station, the data collection in the Paver Station should be as much non-intrusive as possible to avoid delay and disruption of the work.

As shown in Fig. 96.3b, the Paver Station needs to collect and transmit two types of data, namely, coordinate of different target point on the mat and the surface temperature. The surface temperatures can be easily obtained without direct interaction with the surface using infrared temperature linescanner. Infrared temperature linescanner scans a strip of asphalt surface with an update rate between 1 and 150 Hz [16]. The width of this strip is determined by the speed of the paver, i.e., the faster the paver, the wider the strip. This strip is then split into N parts and the surface temperature of each part is measured and recorded by the linescanner. The linescanner is chosen because of its robustness, high update rate and reliability. As for the location data, Global Positioning System (GPS) is mounted on the paver. Both sets of data are sent to the Processing Centre using a router.

96.2.5 Data Analysis, Processing Centre Architecture

As shown in Fig. 96.2, Processing Centre is a station that collects data from both Reference Station and Paver Stations. The main purpose of this centre is to analyze the data and generate real-time 3D temperature contour plots.

Figure 96.4 illustrates the flowchart of the Processing Centre. At the beginning of the project, manager on site defines the temperature thresholds that will be used during data processing. The minimum and maximum temperature thresholds equal lower and upper limits of the compaction window respectively. This setup reduces the computational efforts.

During the main loop of the Processing Centre algorithm the data from Reference and Paver Stations are obtained and analysed in real-time for every time step (Δt). The Paver Station sends TSTs and paver's locations on site, which are filtered and combined by Processing Centre. Then the values for TSTs and TCTs for the paved asphalt section are calculated based on a stream from Reference Station (RSTs and RCTs values) with usage of Eqs. 96.1–96.4. Based on these analysis, the temperature contour plots of the asphalt at a given time are generated. The processed data is then stored in the Processing Centre and presented to interested parties on the site, e.g. the roller operators. Given that the plot is generated in real time, the

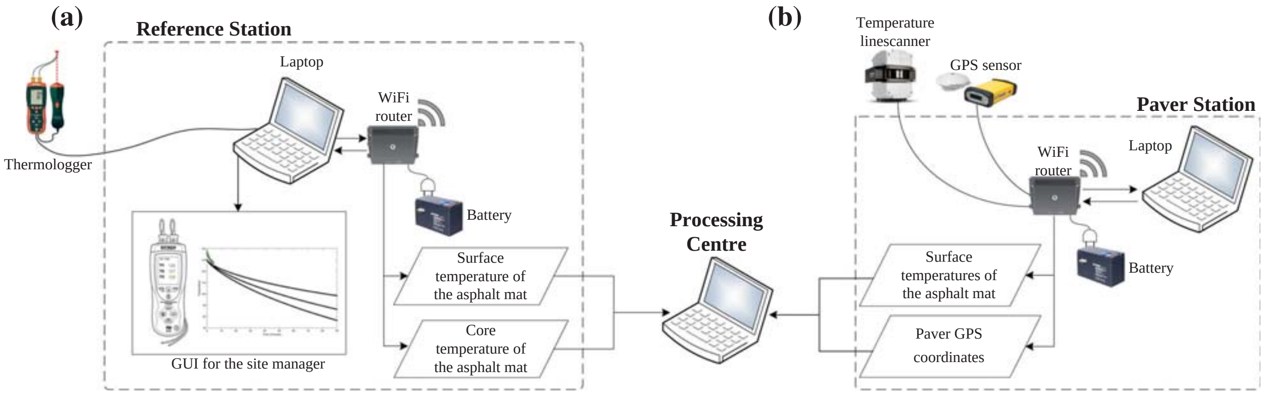


Fig. 96.3 **a** The architecture of the reference station, **b** the architecture of the paver station

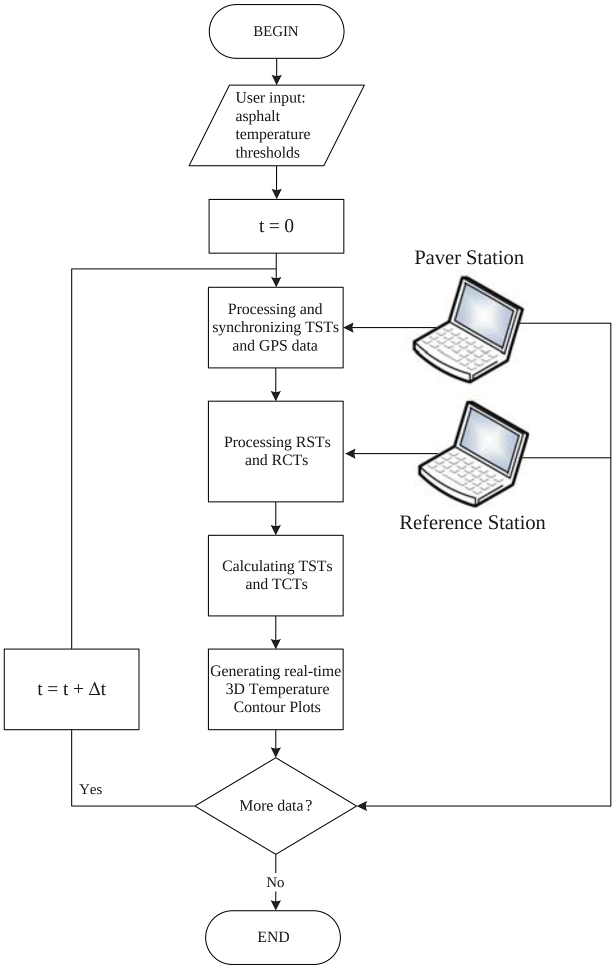


Fig. 96.4 The flowchart of the processing centre

graph dynamically updates to reflect the thermal behaviour of the asphalt. This real-time information enables the roller operators to better pinpoint spots that require compaction more urgently because they are reaching the lower bound of the compaction window. This can considerably reduce the chance of under- or over-compaction of the asphalt mat.

96.3 Implementation and Case Study

A prototype is developed to test and validate the proposed system. In this prototype, the Reference and the Paver Stations are designed and the server of ASPARi research unit at University of Twente, the Netherlands is used as the Processing Centre. Matlab is used to develop all the relevant algorithms and developments.

For the surface and core temperatures collection at reference point, the thermologger Extech HD200 [16] is used. The thermologger feeds the system with data from two thermocouples (i.e., to capture RCTs) and one additional infrared sensor (i.e., to capture RSTs). The MP150 Raytek linescanner [17] is used on the paver to capture TSTs. It was providing the system with the surface temperatures of the asphalt mat during paving procedure. As for the wireless communication, Vodafone MachineLink 4G [18] is used to establish the connection between the Processing Centre, Reference and Paver Stations. The implementation has been tested and validated on several projects since 2015. To provide evidence on the functionality of the system, a case study carried out in collaboration with Roelofs, the Dutch asphalt construction, on the N228 road (Montfoort, the Netherlands).

Figure 96.5a shows the setting of the project. The project was the construction of the road surface layer with stone-matrix asphalt mixture. During paving and compaction activities, two asphalt teams were involved. Before the start of the project, the temperature reference point for the thermologger setup was identified and the sensor was installed, as shown in Fig. 96.5b. The paver of the asphalt team was equipped with the linescanner as shown in Fig. 96.5c.

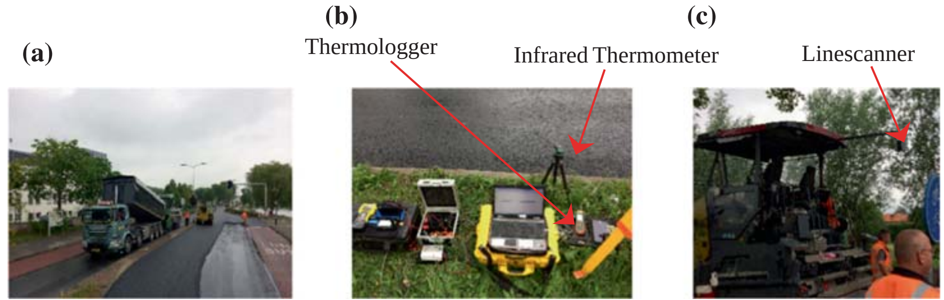
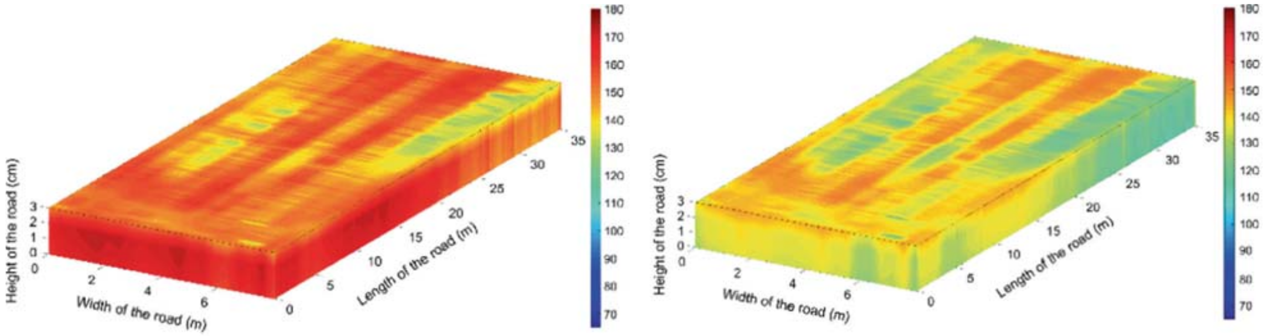


Fig. 96.5 **a** N228 project, **b** setting of the reference point, and **c** installation of linescanner on the paver

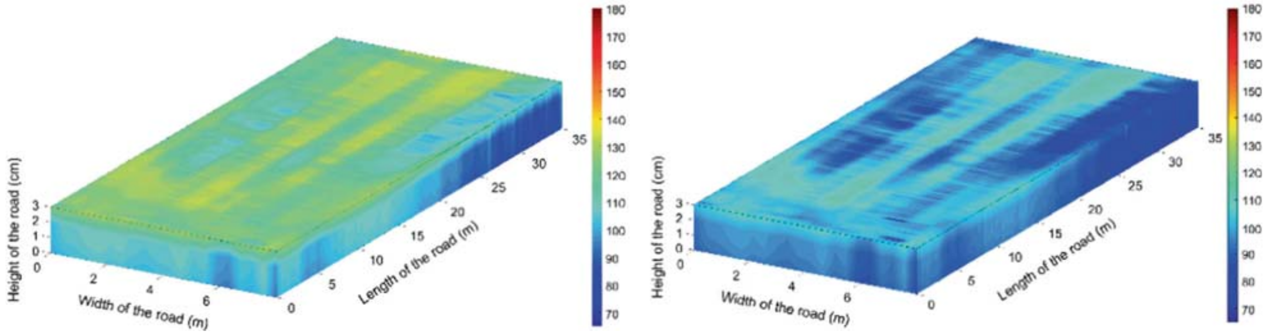
Upon the successful installation of the equipment, the prototype system was run when the pavement operation began. The system successfully generated the 3D temperature contour plots based on the input data from the Reference and Paver Stations with an update rate of 1 s. Figure 96.6a–d shows the snapshots of the plots generated by the prototype. Each 3D temperature contour plot represents the surface and core temperatures along the length, width and the thickness of the paved asphalt section. The three dimensional graphs provide deeper insights into the asphalt layer behaviour after paving and during the compaction. The clear visualization of the surface temperature of the asphalt mat already brings an understanding about the thermal processes that are happening after the asphalt has been re-mixed by paver augers. However, the core asphalt temperatures that are presented in the front and in the profile of a 3D plot provide the real-time thermal condition inside the asphalt mat. This approach of data representation does not depend on the theoretical assumptions about asphalt temperatures during construction, giving abilities for the asphalt team to react accordingly to current situation on site.

For instance, Fig. 96.6a shows that the temperature of the asphalt after paving (130–170 °C) is well above the compaction window for the stone-matrix asphalt mixture (i.e., 80–120 °C). In this situation, roller operators should wait for the appropriate temperature. Figure 96.6b represents the situation 3 min after the paving. Although the temperature of the central part of the road is not optimal for compaction, roller operators may focus on the left and right sides of the road.



(a) at the beginning

(b) 3 minutes after the start



(c) 8 minutes after the start

(d) 15 minutes after the start

Fig. 96.6 Snapshots of 3D temperature contour plots

Figure 96.6c, d indicate the site conditions 8 and 15 min after paving, respectively. Based on these plots, roller operators can focus more to the road center, and avoid passing over the road sides.

96.4 Conclusions

Based on the results of the case study, it can be concluded that there is a possibility to build 3D temperature contour plots of the laid asphalt. Relying not only on surface or core temperatures of an asphalt layer, but simultaneously collecting real-time values of both of these data sources, the system prototype can measure and visualize the temperature gradient within the asphalt layer efficiently. This provides the machine operators with appropriate visualizations of the current conditions of the asphalt mat. Having such information, equipment operators can improve working patterns in terms of pre-compaction and compaction strategies.

During the implementation of the system prototype on a construction site, all the sensors showed stable and reliable behaviour. Nevertheless, in the current setting, the Reference Station is limited to data from only one spot at the reference point. To make the Reference Station more accurate, a fibre optic sensor can be installed along and/or across the paved section. This can provide more accurate temperature data along and/or across the asphalt mat at the start of paving. Paver Station can be improved by wireless sensor or application of the infrared camera with a wider, in comparison with linescanner, field of view. A thorough comparison between the temperature estimation based on the proposed real-time measurements and the predictive/theoretical models will be conducted in the future.

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