A real-time system for prediction cooling within the asphalt layer to support rolling operations

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ABSTRACT

During the hot-mix asphalt (HMA) paving process roller operators generally rely on personal experience and have little information about the in-asphalt temperature [1] . Information about temperature, however, is important for the final quality of the pavement. HMA mixes need to be compacted within a certain temperature window. Too hot may create corrugations. Too cold may create damage [21]. The introduction of the Warm Mix Asphalt, for reasons of sustainability, affects the compaction practice directly. The operational choices of the roller operator become more critical. Until now most operators assessed temperature on look and feel. A more method based approach is needed. Because the in-asphalt temperature is not easy to predict and measure, reliable real-time information system is necessary. This paper describes the development and first test of such a system.

Continuous surface and in-asphalt temperature measurements are the first step in monitoring cooling of the asphalt layer. When presented in a comprehensible fashion, roller operators can use this information to develop more pro-active compaction strategies. The developed automated temperature unit (ATU) provides real-time surface- and in-asphalt temperature information to roller operators. Implemented system displays measured and predicted asphalt temperature changes as well as the time left before the mix will cool down to the certain temperature. Temperature-related information might assist machine operators in making decisions when to start and when to stop rolling, as it is indicated by the preliminary results. Analysis of recorded temperature data can help to improve paving practices.

Keywords: temperature susceptibility, process control, equipment, compaction

INTRODUCTION

Global road network is an important infrastructure asset with high social and economic value, indispensable for the modern society. Because of the value it is desirable to reduce duration of construction and service activities, and have as little as possible impact to the traffic. To fulfill these requirements construction companies continue to improve their work practice to support longer lifetime of the pavement. As within Dutch paving industry risks shift from road agencies to contractors [2], companies introduce new materials into operational practice.

Over the last decades researchers have developed new asphalt mixes [23], aimed to improve road characteristics and its lifetime. Often new mixtures have particular properties and suggestions for the construction teams, such as to perform compaction within particular temperature window. If compaction will be done when the asphalt layer is colder or wormer the certain temperature it might negatively influence the final result. In practice, choosing start/stop compaction time is normally based on personal experience and uncertain comprehension of the asphalt temperature .Often temperature of the asphalt is estimated based on indirect parameters, such as color of the surface. This way of obtaining data is not reliable, especially during night time operations. Nevertheless, number of road construction project are to be carried during night hours to avoid traffic peak period, making temperature prediction even more difficult. Uncertainties in temperature estimation might result in operational behavior and, consequently, in the final surface of the road.

We are oriented to support operational choices of construction machine operators by providing real-time information of the surface and in-asphalt temperature and predicting cooling rate based on measurement. The developed system calculate estimated time before asphalt layer cools down to a certain temperature, when additional rolling is useless, or even hazardous. Indicated current temperature readings and expected cooling curve is indicated to assist roller operators on site in making well-founded operational decision.

ROLE OF THE TEMPERATURE IN COMPACTION PROCESS

Asphalt technologists agree that the density of an asphalt mixture is one of the most prominent measurements for road quality [1-5]. Reaching a certain desired density optimizes the desired road characteristics, such as stiffness, fatigue, resistance against deformation and moisture [5]. The desired density and quality is reached by the adequate compaction. Researchers and practitioners postulate that the temperature of the asphalt mixture at time of compaction is important for the density and final quality of the pavement [6-8].

Different authors suggest that compaction should be completed in specific temperature ranges, for example, 90 to 100°C [6], have specified maximum temperature for compaction about 130°C [9], or minimum temperatures between 70 and 80°C [9, 10]. There is general agreement that minimum compaction temperature, where the mixture is stiff enough to prevent further reduction of air, varies depending on the mix properties, layer thickness and environmental conditions [11-13]. If the material temperature is too low during compaction, the functional properties (like the texture of the surface) can decrease. The same prevails for the maximum temperature: when the binder is too fluid, rollers will simply displace or “shove” the material rather than compact it. Cracks behind the rolls can originate, the mixture sticks to the rolls, and the rolls sink into the mixture [14]. Timm et al [8] describe these minimum and maximum temperature as an understressed and overstressed situation and the time in between as the optimal compaction frame (compaction window). The general form of the temperature cooling curve is schematically represented in Figure 1 as a function of time. For different mixtures and different conditions, the ideal compaction window shifts along the timescale.

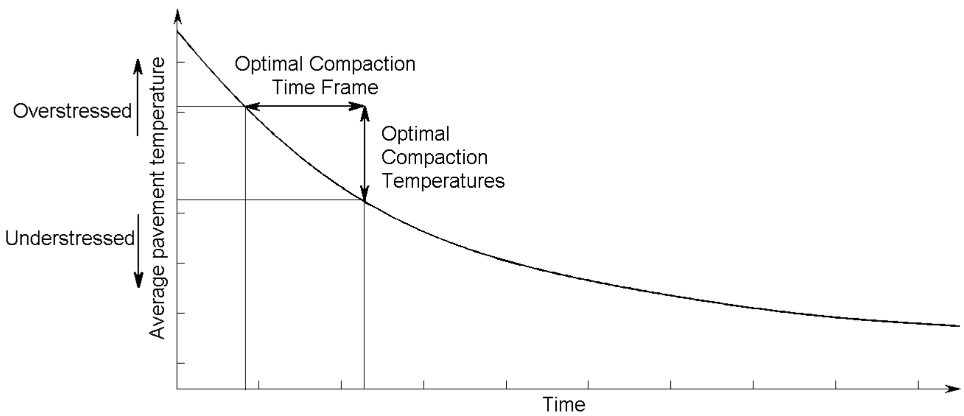

Figure 1: Cooling curve asphalt mixture and compaction window

Traditionally, the optimal compaction temperature was determined through plotting the log-viscosity versus log-temperature plot, when the ideal compaction temperature is the temperature related to the viscosity of 1.7 poise [15]. Subsequently, researchers developed tools to predict a temperature window for compaction based on the viscosity, including the starting and ending temperature to compact [16-18] . Roller operators need information about the cooling of the asphalt mixture, to work within these compaction limits.

Prediction of the cooling curve of an asphalt mixture during the process is a subject of ongoing study. To describe asphalt cooling process researchers previously utilized exponential and logarithmic functions in a general form [1, 2]. Another, more specific formula approaching cooling of asphalt mixtures can be found in the work of Bosseimeyer [19]. Based on the range of possible parameters he defined an approximation formula for different temperature cooling ranges. In particular, new layer cooling rate from 100 to 30% of the lay-down temperature has a form:

$$\zeta_m = \frac{100}{1+0.73\tau^{0.7}} e^{-0.38\frac{1}{\xi_R}\tau},$$

with:

$\tau = \frac{2a}{d^2} \cdot t\ -$ time factor,

$a -$ thermal conducting ability $\left[\frac{m^2}{hours}\right]$,

$d -$ thickness of the layer $[m]$,

$t -$ time $[hours]$,

$\xi_R = \frac{\lambda}{\alpha \cdot d} -$ pole value,

$\lambda -$ thermal conduction coefficient $\left[\frac{kcal}{m \cdot h \cdot °C}\right]$,

$\alpha -$ thermal transition coefficient $\left[\frac{kcal}{m^2 \cdot h \cdot °C}\right]$.

Lately, physical description of the cooling process was introduced in specially developed software tools. With predicted cooling curve for a particular mix, roller operators are able to make well-founded operational decisions to obtain better final quality of the road. Research is conducted to model the cooling rate of the asphalt mixture [20], and concludes that modeling the effects of rain and wind are difficult, while these circumstances are critical for roller operators. Subsequent, Chadbourn et al [7] developed a Windows-based computer program, PaveCool. This is a one-dimensional algorithm to predict the pavement cooling rate. The program takes the following input parameters into consideration to predict the cooling of the mixture:

- type of the existing surface, the material conditions (dry/wet/frozen/unfrozen) and the surface temperature;
- type of mixture, binder properties and the delivery temperature;
- the layer thickness;
- the environmental conditions: ambient temperature, wind speed, cloud cover and latitude;
- the desired temperature to start and stop compaction;
- the time of the year and time of day.

The PaveCool program calculates a theoretical cooling rate for the mixture and recommends starting and ending time for compaction after lay-down based on the desired temperature to start and stop rolling. To determine these start and stop temperatures for different mixtures under varying conditions laboratory procedure was suggested [21]. Further development of the PaveCool program resulted in a software tool named CalCool, that is able to deal with multi-layers [8]. Later, researchers developed practical guides to estimate compaction windows based on local conditions [12,13,22]. One of the Dutch contractors (Ooms Avenhorn Group bv) developed a compaction window for a specific asphalt mixture with modified bitumen. This contractor determined the window in the laboratory and validated it with several field studies [23]. For this example following compaction conditions were determined:

- Compaction with a 3-drumm roller to be done between the temperatures 170-120 °C (app. 50 m behind the paver);
- Compaction with a tandem roller between 120-90 °C (app. 100 m behind the paver);
- Compaction with a 3-drumm roller between 90-60 °C (app 200-300 m behind the paver).

The overall goal of models, programs and methods described above is to provide asphalt teams and decision makers with information about the temperature during the compaction process in order to have an impression of the available time for compaction. Described methodologies give prediction for the cooling rate based on input parameters, existing in the moment of pavement and require additional effort to collect them. However, during construction projects a number of factors may influence the compaction time, such as change of the wind speed, rain, varying layer thicknesses, etc. In all those cases differences arise between predicted (models) and real asphalt cooling rate and result in difficulties for operators to predict the material temperature and adjust their operations according to the 'ideal compaction window'. Therefore, real-time information about the temperature of the mixture should be provided to roller operators.

Moreover, temperature across the layer thickness is rarely constant. The surface of the layer cools down faster than the middle of the layer and also the temperature at the bottom of the layer can decrease faster as it depends on the temperature of the underground. For example, it could happen that the middle of the layer is still too hot for compaction, while the surface of the layer already has a temperature suitable for compaction. With technologies, such as lasers, thermocouples and infrared cameras (eventually combined with GPS), it is possible to register the lay-down temperature of the particular region, the cooling rate, the number of roller passes, the temperature at certain roller passes, etc. [1, 20, 21]. Dorée and Miller [24] studied the temperature homogeneity during the compaction process and conclude that laserlinescanners are suitable instruments to measure the homogeneity of the surface temperature and contour plot a good way to visualize surface temperature. Van Dee [20] concludes that in-asphalt temperature can be better measured with thermocouples and the surface-temperature is better measured using infrared cameras. These technologies can assist operators in working, however, this information normally processed and analyzed after the construction project done.

Despite of the available software solutions and technologies, such as thermocouples and infrared cameras to document and analyze the temperature of the asphalt mixture, up to now information regarding the cooling of the asphalt mix is not available to machine operators on site. Still, machine operators are aware of the influence of severe changes to the cooling rate of the asphalt mix. It was shown, that 'Specialists assume that severe meteorological conditions during paving result in accelerated cooling of the mixture and, therefore, in a lower compaction result' [2, p.17]. To adjust their operations, operators need real-time information about the initial temperature and the cooling during the project. This demand requires additional effort to deliver the information in a clear and understandable way and performing the transition from simulation programs and post-processing data analysis to the real time mode. The next section will describe a system for real-time data collection of the cooling of the asphalt mix.

A REAL-TIME DATA COLLECTION AND COOLING CURVE PREDICTION UNIT

To provide insight to the asphalt mix cooling rate we developed a software solution to obtain sensors readings, process and display surface and in-asphalt temperature in real-time and predict cooling curve of the mixture. Temperature information is stored in a database and, using a wireless network at the construction, is accessible to the construction team on site and managers via Internet. The overall architecture of the developed unit and corresponding infrastructure is presented in Figure 2. The central part of this infrastructure is the automated temperature unit (ATU), which consists of the infrared (IR) camera, a measurement device with thermocouples (datalogger) and a processing unit. During development process we followed ROPES (Rapid Object-oriented Process for Embedded Systems) model, that include consequents testing, translation, design and analysis tasks, where architecture is of particular reference [25]. Continuously iterations were oriented to test the set-up at a construction site, receive suggestions from practitioners and proceed with further development.

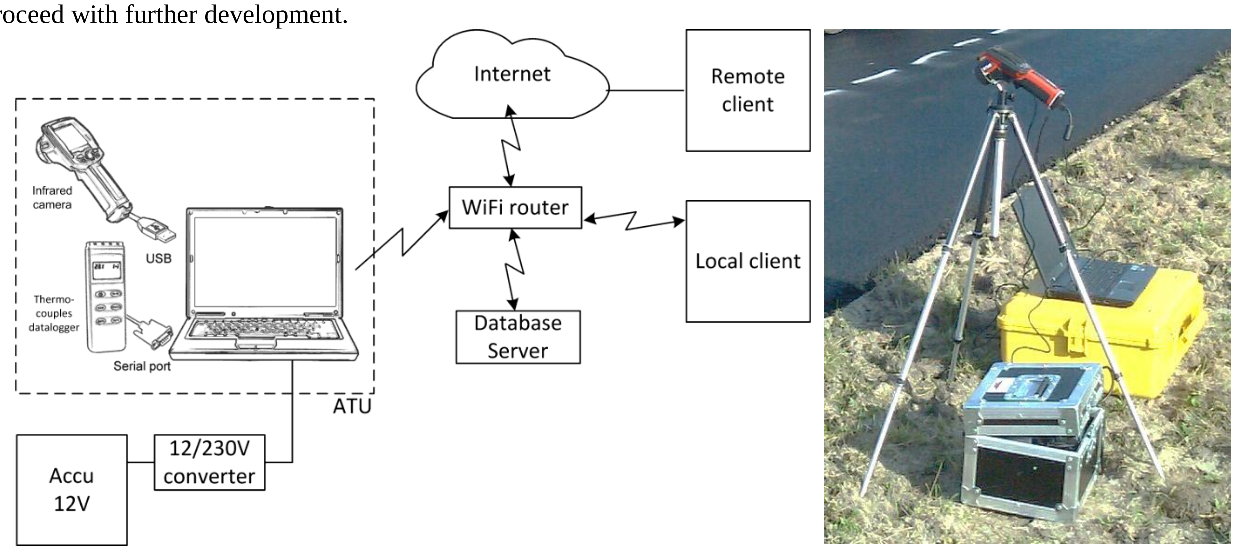

Figure 2. The architecture of the developed automated temperature unit and prepared ATU before the paver pass

Prepared ATU before the paver pass is displayed on Figure 2. Thermocouples and IR camera can be used at any position after the paver, next to the side of the road. After a paver passes the proposed measurement point we inject the thermocouples into the asphalt layer and aim the infrared camera position to the corresponding spot. The infrared camera automatically adjusts level and span of the IR image, indicating lowest and highest temperature within the scope. We assume that such averaged information of the temperature distribution on a relatively small area provides adequate information about the asphalt surface temperature. To obtain in-asphalt temperature we utilize measuring device, capable to obtain and store readings from up to four thermocouples. This combination is able to provide reliable measurements even if any of the probes or wires would be damaged after a roller pass. Using this sensor set-up we are able to obtain continuous readings of the surface and in-asphalt temperature. To save the temperature information for future reference infrared images are stored in IR camera's memory at the moment of measurements and readings from the thermocouples are continuously saved in inner memory of the corresponding device. Temperature measurements, periodically obtained from the IR cam and thermocouples, are stored in a database and used for predicting the material cooling curve.

In general, both measuring components of the ATU have a form of 'smart' sensors, able to obtain an analog signal as input, process and transmit a final output in digital form. Continuous nature of data collection and four available inputs from the datalogger require data fusion solution, that can be characterized as fusion across sensors, when a number of sensors nominally measure the same property [26]. Fusion across in-asphalt sensors is implemented by selecting maximal temperature from four available thermocouple measurements.

To predict continuous mixture cooling based on in-asphalt sensors readings it is necessary to find a suitable fitting function for the cooling curve. For this purpose we utilized Matlab software with the Curve Fitting Toolbox to find 'pole value' and 'time factor' parameters of the cooling curve [19]. Calculations start in a few minutes after a new layer was constructed. Minimal and maximal limits of the 'pole value' and 'time factor' variables are fixed and curve fitting task is to find exact values within the certain ranges. Obtained numerical values correspond to the certain period of time, within which the weather conditions may change. Based on the obtained temperature curve and the known asphalt compaction window the ATU is able to predict time, while the asphalt mix will still have the desired temperature for rolling (Figure 3). Continuous fitting function calculations and automated time factor and pole value calculations are aimed to predict cooling curve without requirement to set number of parameters, e.g. ambient weather conditions. Prediction of the cooling curve and expected time of cooling to the certain temperature is displayed on a screen along with the latest surface and in-asphalt temperature readings.

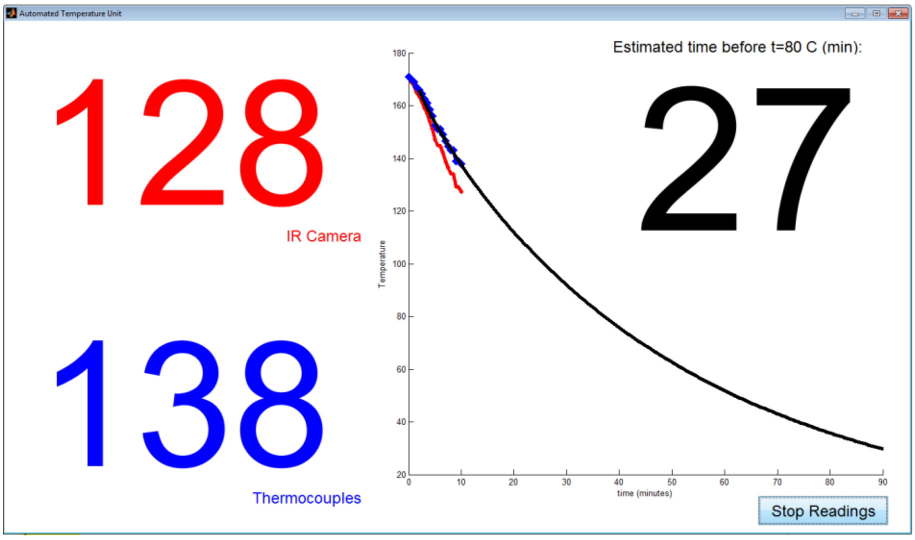

Figure 3. Example of the running program

Surface temperature readings, obtained by the infrared camera, are displayed to show particular difference between surface and in-asphalt temperature to provide insight of cooling in general. The indicated in-layer temperature information, predicted cooling curve and estimated time, when temperature would be above the certain degree, are oriented to give roller operators reliable information regarding current temperature and expected cooling. This information could assist machine operators in making well-founded decisions when to start/stop rolling. Given figures along with the sensors readings, stored in a database, are available at the screen next to the measurement point and via wireless connection at any computer on a construction site and outside of it.

As the installation of ATU implies only injection of thermocouples into the asphalt layer, deployment of the datalogger device and the infrared camera, those operations can be done within a minute and does not require any special knowledge. By obtaining real-time temperature readings from the asphalt layer the ATU prediction do not rely on the measurements of ambient weather conditions, or other contextual information. With its continuous calculation of the cooling curve, based on actual data, the ATU overcomes the shortcomings of other software simulation programs, which rely on the temperature prediction in advance and have no ability to react on changes in weather.

Initial experiments with deployed ATU at an actual road construction site and interviews with machine operators indicated potential value of this system. Operators perceive this system as useful and easy to use and respond that they can increase the speed of conducting their tasks and their efficiency. At the same time, as the system is showing temperature at one particular spot it is hard to project this information to the whole surface. To overcome this limitation, additional research is necessary in order to assist operators in their everyday tasks.

CONCLUSION

Asphalt pavement is a complex process that involves different machinery and often is restricted in time. Machine operators are immediate participants of the process and directly influence the asphalt layers, critical for the lifetime of the road. Although in contemporary paving practice the demand for high quality pavements is rising continuously, road construction processes in practice are strongly based on previous experience of the operators. To support rolling operations in different conditions, at night and with new asphalt mixtures additional information might be desirable.

Theoretical knowledge of improving optimal pavement processes might be effectively linked with practice at the road construction site. To improve asphalt pavement operations a number of suggestions were developed in laboratories, including suggested start and stop rolling according to specific temperature limits. Those suggestions are oriented to roller operators, but it is hard to estimate current temperature in real conditions and the rate of asphalt cooling. To deliver current layer temperature information to roller operators in a convenient way additional effort is needed. To address this issue we developed an automated temperature unit (ATU) to measure surface and in-asphalt temperature, process data and make prediction of the asphalt cooling rate in variable weather conditions. This unit collects data in a non-intrusive way with less configurations in comparison to existing temperature simulation programs and provides temperature information to roller operators on site. Continuous temperature readings and updates of the cooling curve are oriented to provide actual information in changing weather conditions. Developed ATU displays real-time surface and in-asphalt temperature based on continuous readings from infrared camera and thermocouples, predicts further cooling of the asphalt mix and the time, before temperature will stay above curtain degree. Displayed data is oriented to support roller operators in making decisions when to start/stop rolling procedure according to the suggested temperature limits for the asphalt mix.

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