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Abstract

A uniform temperature of the newly laid hot mix asphalt (HMA) mat is crucial for achieving adequate compaction and ultimately for the performance of the pavement. The compaction is influenced by numerous factors, and the most critical factors appear to be those that affect the HMA temperature and cooling rate. The infrared thermography can be used as a means of quality control during HMA paving. As shown in this case study infrared thermography was able to determine the temperatures of HMA in truck prior to dumping in the paver and clearly discern temperature differentials on HMA mat behind the paver.

1. Introduction

Increase in traffic loads world-wide has led to demand to build more durable and longer lasting pavements. Due to its numerous advantages, such as its ability to withstand heavy traffic under various environmental conditions, its cost efficiency and its recyclability, hot mix asphalt (HMA) has been the “pavement of choice” for over forty years [1]. From the first installation of HMA pavement till today mix designers continue to work on the improvement of the durability, rutting resistance, and resistance to fatigue cracking. However, no matter how well the mix is designed, if it is not compacted properly, it will not perform as expected [2].

The need for adequate compaction has been recognised since the early days of HMA pavement construction, and it is generally acknowledged that this is most important factor associated with pavement long term performance [3, 4]. There are many factors that affect the ability to achieve adequate compaction of HMA in the field. These factors are related to mix characteristics (gradation, maximum aggregate size, binder stiffness etc.), environmental factors (ambient temperature, base temperature, wind speed, solar radiation etc.) and construction characteristics (production, laydown and compaction temperature, number, type and passes of rollers, lift thickness, haul distance, confinement etc.) [5]. Most of these factors directly influence production, laydown or compaction temperature of HMA [6]. Temperature has been long recognised as a critical compaction factor and for any HMA mixture compaction must take place within a temperature range in which the binder is sufficiently fluid to allow reorientation of the aggregate particles [7]. For successful construction of HMA pavement, each step in production and construction process must be carried out within the specified temperature range. If the laydown temperature of HMA mat is inconsistent, the degree of compaction will vary. Variations in density of HMA pavement caused by temperature differentials are referred to as temperature segregation [8].

Current regulations in Croatia require quality control of HMA temperature during construction in accordance with HRN EN 12697-13 [9]. According to this standard, the HMA temperature must be measured after mixing and during storage, transportation and placement using a contact thermometer or an infrared thermometer at randomly defined sampling locations. The data obtained in this way provides information about the temperature at selected locations so areas of low temperature can easily be overlooked. If quality control is carried out in this way, it is very likely that areas affected by temperature differentials will not be detected. An alternative to the use of thermometers is the use of infrared thermography which allows for continuous, real time data collection during paving process.

This paper presents a case study in which infrared thermography was used to identify temperature segregation during different construction phases and to determine possible causes of temperature differentials as a quality control measure for HMA paving.

2. HMA compaction temperature

The basic objective of compacting HMA is to reduce the volume of air by using external forces to reorient aggregate particles into a more closely spaced arrangement and thus increase the density [10, 11]. For dense graded HMA, air voids between 3% and 8% generally provide the best compromise between pavement durability, fatigue cracking, rutting, ravelling and susceptibility to moisture damage. When the in-place air voids decrease to less than 3%, rutting and shoving of the HMA pavement is likely to occur. When the air voids are above approximately 8% the HMA pavement is permeable to air and water resulting in water damage, oxidation, cracking or ravelling [5, 11]. In their study, Linden et al [12] concluded that every 1% increase in air voids over the base level of 7% results in approximately 10% loss in pavement life, which is about one year.

HMA mixtures are traditionally produced at relatively high temperatures between 150 and 180°C [14, 15]. During the transport from plant to construction site HMA will cool down and cooling rate depends on ambient temperature, wind speed, haul time and distance. HMA mixtures are usually placed at temperatures between 135°C to 150°C for unmodified HMA and 140°C to 160°C for polymer modified HMA [2]. During placement HMA is initially compacted by the paver screed. Depending on the screed type, mixture density after laydown can be between 75% and 85% of relative density [15]. After the mix is placed, the temperature is lost in two directions downward into the base and upward into the air. The cooling rate depends on layer thickness, air temperature, base temperature, mix laydown temperature, wind speed and solar radiation [15]. The next phase of the compaction process, roller compaction, aims to achieve adequate density and to provide smooth surface. These two objectives are accomplished through use of breakdown and intermediate rollers to achieve adequate density and finish roller to remove roller marks. If the desired density can be achieved by breakdown roller, an intermediate roller may not be necessary. Rolling should be carried out at the highest possible temperature to achieve an adequate density with minimum compaction effort. Breakdown and intermediate compaction must be accomplished before the mat cools to a temperature below approximately 80°C, called the cessation temperature [11]. At temperatures near 80°C (may vary somewhat depending on binder grade) the probability of significantly reducing air voids is very low [11, 15].

The temperature range to achieve adequate density of HMA pavement is between mat laydown temperature and cessation temperature. Incorporating cooler HMA into a pavement mat during laydown results in creation of concentrated areas that are referred to as temperature differentials and that can result in temperature segregation [16].

3. Temperature segregation

One of the most common and costly problems associated with HMA pavement is segregation [17, 18, 19, 20]. Segregation is defined as ˝...lack of homogeneity in the HMA constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress(es)˝ [21]. Constituents should be interpreted as bitumen, aggregates, additives, and air voids. Segregation is generally divided into two categories, aggregate segregation and temperature segregation. Aggregate segregation is a concentration of either coarse or fine material in some areas of the paved mat. These areas are often characterized by different surface textures from the surrounding material and usually can be seen by eye. Temperature segregation is a localized area of lower than desirable pavement density caused by temperature differentials in the HMA mat [22].

The term temperature segregation was introduced in the late 1990s [23]. In his master's thesis Read [24] investigated factors that could be associated with "cyclic segregation" or "end-of-load segregation" and discovered that not all sections that exhibited lower density had aggregate segregation. This type of segregation was found to be related to differentials in temperature of the HMA mat. He found that large temperature differentials could occur to such an extent that the resulting densities of the compacted mat were lower than desirable. Based on his conclusions, research programs using infrared thermography were initiated to investigate the existence and extent of temperature differentials and their effect on HMA pavement properties [1, 16, 17, 21, 23, 25, 26, 27].

Temperature differentials were defined as "…the difference in average mat temperatures between a concentrated "cooler area" and the surrounding "normal area" and are related to the changes in quality of HMA pavement" [23]. Based on temperature differentials observed during laydown of HMA mat Stroup-Gardiner and Brown [21] defined four severity levels of temperature segregation. Temperature segregation levels in relation to air void content and temperature differentials are presented in table 1.

Table 1. Temperature segregation levels [21, 28]

No segregation	**Low-Level Segregation**	**Medium level segregation**	**High level segregation**
Acceptable air voids	Increased air voids of between 0 and about 4 percent above acceptable	Increased air voids of between 2 and about 6 percent above acceptable	Increased air voids more than 4 percent above acceptable
Area in the mat with temperatures 10°C or less of a difference between coldest and hottest temperatures	A discrete area in the mat with a mean temperature between 11 and 16°C cooler than the surrounding area	A discrete area in the mat with a mean temperature between 17 and 21°C cooler than the surrounding area	A discrete area in the mat with a mean temperature more than 21°C cooler than the surrounding area

Through the use of infrared thermography, it became clear that the temperature differentials during paving operations are much greater than previously assumed and that, although they have not been detected, they have been a significant problem for many years [1].

Pavement temperature differentials result from the concentrated placement of a cooler mass of HMA into the mat. This cooler mass is generally associated with cooling of HMA in a haul truck during transport. The cooler mass is usually dumped to the extreme left and right sides of a paver hopper in the wings and is the last to exit the hopper [29]. The heat loss begins to occur around the perimeter of the truck immediately as the HMA is discharged into the truck. Factors that influence the amount of heat loss and temperature differentials are HMA temperature when loaded, ambient air temperature, truck characteristics (insolation, size of truck bed in relation to mix hauled, use of tarps), haul time (haul distance, speed of travel, traffic delays) and waiting time at paver [1].

There are two distinct patterns of temperature differential distribution on HMA mat: cyclic and irregular [1, 16, 23, 30]. Cyclic temperature segregation appears as a consistent cyclic occurrence of temperature differentials with a certain interval. It is attributed to the cooling of asphalt mixtures during normal paving operations [23]. Irregular temperature segregation occurs at indefinite intervals when the paving operation is stopped for a longer period and the wait time was long enough to cool the uncompacted mat significantly [22].

To help identify a specific shape type and probable causes of temperature differentials, and to suggest solutions Putman and Amirkhanian [19, 20] have introduced temperature segregation field guide that is summarised in table 2 [23, 28]. Figure 1 shows an example of the types of temperature segregation.

Table 2. Summary of temperature segregation field guide [19, 20, 23]

Type	Causes	Solution
Cold Joints	Time delay Work stoppage Temperature differentials between truck load	Ensure equipment functioning Maintain steady pace
Truck end	Improper loading of HMA in truck Long haul distance Truck traps are not used	Proper loading of haul tracks Use of material transfer vehicle Reduction in haul distance
Wing Dumps	Dumping the cooler material at the paver wings after each truck load	Use of material transfer vehicle Not dumping or more frequently dumping of paver wings
Streaks	Malfunction of paving equipment, namely the paver screed	Check operation and function of paver at specific intervals Fixed malefaction as quickly as possible
Cold spots	Laydown of cooler HMA into mat without proper remixing in the paver Building up of HMA in the paver	Use of material transfer vehicle Use of truck tarps Ensuring proper functioning of the paver

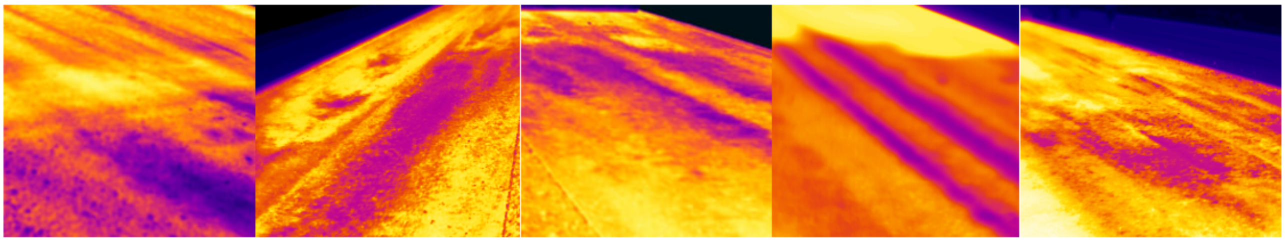

Figure 1. Types of temperature segregation (from left to right): cold joint, truck end, wing dumps, streaks, cold spots [19, 28]

Based on the prior research efforts it can be concluded that because many factors are involved with paving operations, no single piece of equipment or operation will guarantee that temperature segregation would not occur [16]. However, there are techniques that can be utilized to offset the effects of temperature segregation, and these are: the use of proper insulations for hauling trucks, minimizing waiting time, use of material transfer vehicles, careful hopper wing control, timely compaction and use of pneumatic rollers as breakdown or intermediate rollers [16, 17, 25, 29].

4. Zagreb Airport case study

As already mentioned, the objective of presented study was to utilize an infrared thermography to identify temperature differentials in HMA pavement which could affect compaction and lead to premature distress of the pavement.

The measurements were performed on June 18th, 2011, between midnight and 03.30 am. The air temperature during the examination was 13°C at the beginning of the test and dropped to 10°C towards the end of testing. The sky was cloudy, and it started to rain slightly at the end of testing, which caused the termination of the paving process.

Temperature data was obtained using an FLIR P640 infrared camera (thermal sensitivity 60 mK, geometric resolution 640x480 pixels, FOV 24°).

Infrared camera was used to determine the temperature of the HMA during dumping process in order to estimate the possibility of its proper placement. Figure 1 shows the HMA mix in the truck at the beginning of the dumping process to the paver.

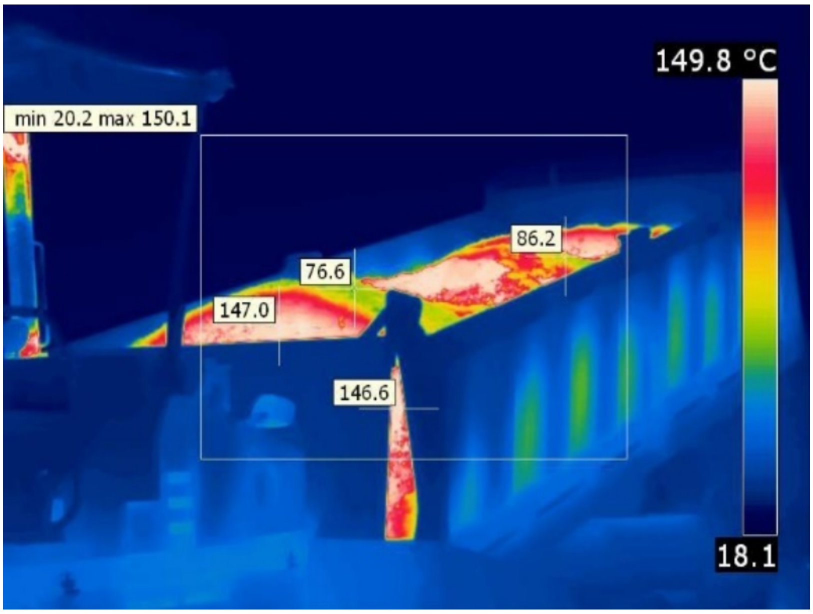

Figure 2. Thermogram of the beginning of HMA mix dump into the paver

From the figure 2, it can be seen that cold crust formed on the top of the HMA, the temperature of the cold crust is between 76.6 and 86.2 °C while the temperature of the HMA below the cold crust was 147°C. Thermogram shows that HMA of cooler temperatures is being dumped into the paver; this creates pavement temperatures near cessation temperature. In the case of this specific site, the reason why the cold crust was formed was waiting time before the HMA could be dumped to the paver, since haul distance was very short it didn´t influence as much.

After the paving, cool areas of uncompacted HMA mat were clearly discerned at the paving site, figures 3 and 4.

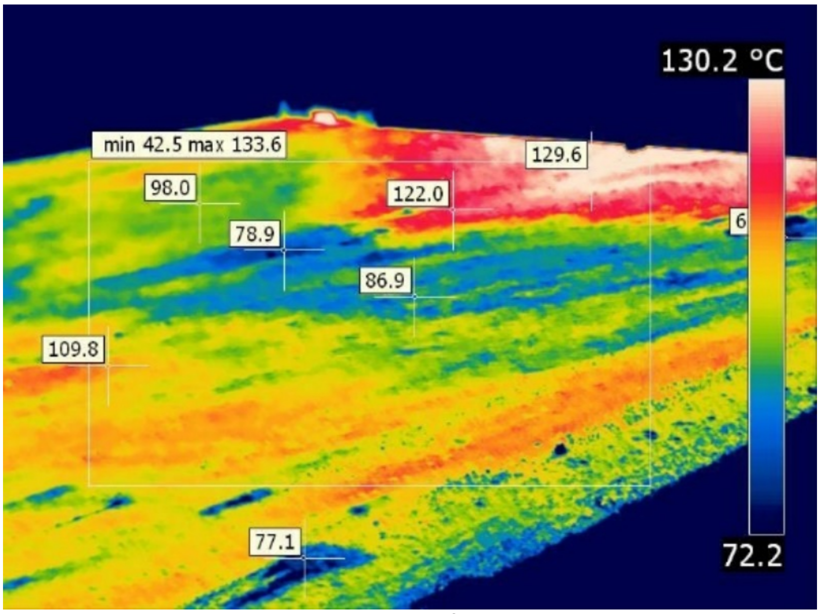

Figure 3. Thermogram showing end of load temperature segregation

Figure 3 shows the characteristic temperature segregation pattern that cyclically appears in the pavement after the end of dumping and with the change of trucks. The temperatures measured were very close to cessation temperature (80°C), in few places even lower (78.9°C). With the additional cooling of the HMA before finishing of the compaction process, it can be assumed the sufficient compaction of the pavement will not be achieved.

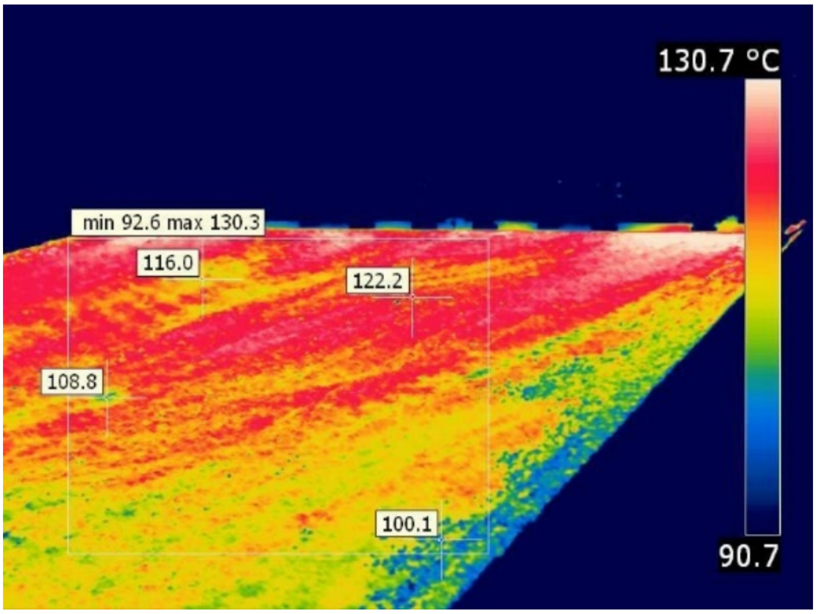

Figure 4. Thermogram showing minimal temperature differentials in a HMA mat

Figure 4 shows the area of uncompacted HMA mat with minimal temperature differentials over the whole encompassed surface. The minimal measured temperature is higher than 100°C. The temperature differential over the surface is around 15°C, while lower temperatures are found only on the edges of paved surface were crumbled over spilled material was pushed back in the area that will be compacted.

5. Conclusions

Segregation of HMA has been a problem in the paving industry for many years, but it was only through the use of infrared thermography that it was discovered that the majority of the problem was related to the inadequate temperature of the HMA at various stages of construction process. Through the use of infrared thermography, it became clear that the random variations in density of HMA pavements, i.e. temperature segregation, were caused by the concentration of cold HMA in the mat. Temperature segregated areas of HMA pavement are more permeable to air and water, which eventually leads to premature pavement failure due to water damage, oxidation, cracking or ravelling.

The traditional method of measuring HMA temperature for quality control during pavement construction is to use contact or infrared thermometers at randomly defined sampling locations. If quality control is carried out only at random locations, it is likely that areas affected by temperature differentials will be easily overlooked. To ensure proper quality control HMA temperature could be measured using infrared thermography. The advantage of infrared thermography is the ability to measure the HMA temperature in real time during the various stages of pavement construction and to thermally characterise the entire mat surface, allowing the contractor to remedy problems as they occur. In combination with GPS, it is possible to map the temperature characteristics of the entire pavement, identifying areas that should be monitored over time to observe their performance.

In the presented case study, an infrared camera was used to monitor the HMA temperature of as the mix was discharged from the truck to the paver and during the laydown prior to compaction. Temperature differentials were observed in the haul truck and were related to the waiting time on construction site due to paving delay. The introduction of this cooler material into HMA mat during laydown was identified on a thermogram as temperature segregation at the truck end. Lower HMA temperatures were also observed near the edges of the paving surface and were related to the pushing the loose mix onto the mat surface.

Although research efforts carried out since the mid-1990s show that monitoring the temperature profile of the HMA mat during paving in real time using infrared thermography represents a remarkable advance in the quality control of pavement construction, it is still not accepted as a routine measure. The main reasons behind this are cost considerations, a lack of specifications and complexities with accurately referencing the thermal image with a location on the pavement.

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