Scottish Road Research Board

DEVELOPMENT OF AN AUTOMATED COMPACTION CONTROL SPECIFICATION

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EXECUTIVE SUMMARY

Digital technology has the ability to improve the way asphalt roads are constructed and maintained. The application of technologies, such as remote monitoring and telemetry, can be used to improve the quality control of asphalt materials during the construction phase. Real-time data can be utilised to track the movement and arrival of delivery vehicles, and monitor material temperatures at various stages of the paving process. Heat maps can be produced to assess temperature uniformity and aid the identification of cold material that may resist proper compaction. Specially equipped rollers, fitted with remote sensors, can record temperatures during the compaction process and record the number of passes, including the number of passes covered on different areas of the mat.

Transport Scotland has been exploring how this emerging digital technology can be used to improve the quality of asphalt paving and as a possible alternative to traditional compliance testing. The latter utilises coring and measurement devices which are labour intensive. This study builds on previous work with the aim of developing notes for guidance and compliance requirements for electronic data monitoring. The ultimate goal is to use digital technology to replace test methods that are both destructive and time-consuming and to create a safer working environment for road workers.

The report includes an international literature review which provides an overview of the technology and instrumentation which is available to monitor and control the compaction of asphalt road materials during construction. The causes of poor compaction, current best practice, standards and specifications are summarised. The review also considers a recent case study of how electronic construction data is currently collected, processed and presented.

Based on the above work, the report presents draft notes for guidance on electronic data monitoring and outlines a compliance framework that could be used to approve compaction based on electronic data. The latter includes the adoption of a similar approach to that being used in the USA, although certain aspects have been adapted for the type of materials and equipment available in Scotland. Finally, the report recommends that the draft guidance and compliance requirements be applied to forthcoming schemes to determine their effectiveness and whether further amendments are required.

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1

INTRODUCTION

1. INTRODUCTION

1.1. BACKGROUND

Proper compaction of pavement layers is key to the durability of asphalt roads. Presently, compaction levels are typically assessed and monitored by taking cores which is time consuming and can potentially expose operatives to live traffic. The test, by its nature, is destructive and can slow up the surfacing operations that follow.

Digital technology has the ability to improve the way roads are constructed and maintained. The application of technologies such as remote monitoring, telemetry and control systems are increasingly being used by the road industry. It is recognised that improved quality control of road materials at the construction stage can increase the service life of a road. The use of real-time data such as material temperature (heat mapping) and the number of roller passes over a given area of the mat, can be used to ensure compaction levels have been achieved. This type of technology also has the potential to create a safer working environment for road workers involved in maintenance and construction.

Transport Scotland has been exploring how this emerging technology can be used as an alternative to the established method of monitoring and testing asphalt for quality control purposes. Currently road maintenance contracts with a value over £250,000 and new build contracts are required to collect electronic data as part of pavement construction. Clause 976AR relates to electronic data monitoring during pavement maintenance schemes and Clause 977AR relates to pavement works on new build contracts. This study builds on the work carried out to date with the aim of developing notes for guidance and compliance requirements for electronic data monitoring. The ultimate aim is to use real-time data to monitor and assess the compaction process and replace existing testing methods.

1.2. SCOPE

The Scottish Road Research Board (SRRB) commissioned WSP to develop notes for guidance on electronic data monitoring and compliance requirements that could be used to approve the correct level of compaction. It was agreed that the study would include the following tasks:

- Literature review
  - A review of available information on technology and instrumentation that has been used to monitor and control the compaction of asphalt material, including an overview of the causes of poor compaction, current best practice, standards and specifications.
- Electronic data analysis
  - An examination of electronic construction data that has been collected in accordance with Transport Scotland requirements to identify factors that relate to an acceptable level of compaction being achieved.
- Consultation and Trials
  - Site visits and regular meetings with the Transport Scotland Pavement Forum (TSPF) Automated Data Capture subgroup to ensure industry buy-in and available expertise.
- Reporting
  - A report describing the study, including draft notes for guidance and compliance requirements for electronic data monitoring.

2

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1. OVERVIEW

Achieving the correct level of compaction is critical to the performance of an asphalt pavement. Compaction is described as the process of reducing the volume of a mass of material. For asphalt this typically involves reducing the volume of air in the mixture. Although a mixture can be designed in the laboratory to possess a low air voids content, adequate compaction on site is required to achieve this aim[1]. Road rollers exert forces that adjust aggregate particles into a more closely spaced arrangement and the ultimate aim of compaction is to achieve the target air voids content of the asphalt mixture. It is also important that the compaction level within the layer is uniform in all directions and this is assisted by ensuring the asphalt mixture is homogeneous, i.e. possesses a consistent mixture composition.

The benefits of compaction have been well documented[2] and include an increased resistance to permanent deformation, fatigue loading and moisture related damage. A study in the USA produced a rule-of-thumb or broad guide that for every 1% increase in air voids above the target (typically 6 to 7%), pavement life could be reduced by 10% [3]. The study was based on a survey of 48 state highway agencies on compaction practice, with the primary goal to estimate the effects of air voids. However, it should be noted that for some mixtures a low air voids content (<3%) can be detrimental. In summary, air voids contents that are either too great or too low can cause a reduction in pavement life.

2.2. MEASURING COMPACTION

2.2.1. AIR VOIDS CONTENT

As compaction is required to reduce the volume of air in asphalt, the main characteristic of concern is the air voids content of the compacted pavement layer. The air voids content is calculated in accordance with BS EN 12697-8[4]. The density of core extracted from a compacted pavement is compared with the density it would theoretically have if all the air voids had been removed, known as the maximum density. Air voids content testing is generally considered to be the most accurate but it is also the most time consuming, destructive, expensive and can potentially expose operatives to live traffic.

An alternative to coring is to use a non-destructive measurement device, such as a nuclear or electric gauge. Accurate calibration of these devices with extracted core densities is essential. In the UK, it is common to use a combination of measurements from both cores and indirect density gauges. The devices are typically used to augment the data between core locations. In general, indirect density gauges typically penetrate to a depth of about 80 mm and for thicker layers it is

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[1] Nicholls J C, McHale M J and Griffiths (2008) Road Note 42: Best practice guide for durability of asphalt pavements. TRL RN42. Crowthorne: TRL Limited.
[2] Tran N, Turner P and Shambley J (2016). Enhanced compaction to improve durability and extend pavement service life. NCAT Report 16-02R.
[3] Linden R, Mahoney P and Jackson N (1989). Effect of Compaction on Asphalt Concrete Performance. Transportation Research Record TRR 1217.
[4] BS EN 12697-8. Bituminous mixtures – Test methods for hot mix asphalt – Part 8: Determination of void characteristics of bituminous specimens. BSI.

recommended that the cores used for calibration should be visually inspected to ensure that they are uniform throughout their depth (BS 594987, 2017)[5].

A study aimed at identifying new innovative technologies[6] (D'Angelo G, 2019) for testing and monitoring asphalt pavements, highlighted PaveScan as an alternative method of measuring in-situ density. Shown in Figure 2-1, the PaveScan system is a manually propelled Ground Penetrating Radar (GPR) system. Developed in the USA in 2013, the system is different from traditional GPR systems in that it uses smaller and lighter antennas. It is reported that the system is currently unable to measure the density of thin layers (< 25 mm), and results can be affected by water and temperature. However, the PaveScan is regarded to show potential and could be mounted to a roller providing real time data that could be used to identify poorly compacted material.

Figure 2-1 - PaveScan (Courtesy of GSSI, Geophysical Survey Systems, Inc.)

[5] BS 594987:2015+A1. Asphalt for roads and other paved areas specification for transport, laying, compaction and product type testing protocols. BSI.
[6] Dangelo, D (2019). Sub-Task 2: Evaluation of QC and QA Test Methods. Collaborative Research: Highways England, Mineral Products Association and Eurobitume UK.

2.3. FACTORS AFFECTING COMPACTION

There are many factors that affect the level of compaction achieved in asphalt mixtures. The Texas Department of Transportation Pavement Manual[7] states that compaction is influenced by a myriad of factors which can be broken down into three groups: environment, mix design and construction. Table 2-1 is based on an extract from the TxDOT Manual which highlights the factors that can affect compaction. The table highlights that compacting asphalt is an intricate process with multiple interdependencies. Indeed, constructing asphalt is often described as a combination of science and art. In terms of environmental factors, the location of the works will be fixed but particular attention needs to be given to wind speed which has a greater effect on the rate of cooling than ambient temperature[8]. To some extent, mix properties are fixed before construction although the gyratory compactor is considered to be a good laboratory test to assess the compactibility of asphalt and achieving the target mixture density or air void content in the field. Of all the influences, construction factors are the most controllable. Although factors such as hall distance, production temperature, lift thickness and compaction plant are prearranged, it is the timing of rolling, speed, rolling pattern and number of passes that can be managed for the conditions on site.

Table 2-1 – Factor affecting compaction (TxDOT, 2021)

Environmental Factors	**Mix Property Factors**	**Construction Factors**
Temperature	Aggregate	Rollers
• Ground temperature • Air temperature • Wind speed • Solar flux	• Gradation • Size • Shape • Fractured faces • Volume	• Type • Number • Speed and timing • Number of passes • Lift thickness
	Binder	Other
	• Chemical properties • Physical properties • Amount	• Production temperature • Haul distance • Haul time • Foundation support

2.3.1. TEMPERATURE

Temperature of the asphalt mixture has a major effect on whether a contractor will achieve the desired level of compaction. As temperature decreases, the binder becomes more viscous or stiff. It eventually reaches a stiffness which prevents further compaction or reduction of air voids, regardless of the applied compactive effort. Commonly known as the cessation temperature, it is dependent on the particular mix volumetrics (especially binder properties), layer thickness and weather conditions.

[7] TxDot (2021). The Texas Department of Transportation Pavement Manual. http://onlinemanuals.txdot.gov/txdotmanuals/pdm/compaction.htm
[8] Daines M (1985). Cooling of bituminous layers and the time available for compaction. Research Report 4, TRRL. Crowthorne: TRL Limited.

A study in the Netherlands[9] used infrared cameras, line scanners and sensors to study asphalt temperature characteristics on live construction sites. The study showed that thermal imaging, using temperature contour plots, can improve the quality control of paving and compaction processes. The study also highlighted that, although mid-depth material layer temperatures were higher than surface temperatures, there was a strong correlation between the two and surface temperatures could be used as a predictor of material core temperature.

BS 594987 specifies minimum rolling temperatures for a range of asphalt mixtures. These temperatures relate to the cessation temperature described above and require the rolling to be substantially completed prior to this temperature being achieved. Examples of the range of temperatures provided in BS 594987 for different materials is given in Table 2-2. The standard notes that different temperatures may be applicable, particularly when mixtures utilise modified bitumen or additives.

Table 2-2 – Rolling temperatures (BS 594987)

Mixture	**Paving grade bitumen**	**Minimum rolling temperature**	**'Recommended' minimum temperature immediately prior to rolling**
HRA	40/60 pen	85°C	105°C (110°C for surface coarse)
	70/100 pen	80°C	90°C
AC (designed binder course and base)	40/60 pen	105°C	105°C
	70/100 pen	90°C	90°C
	15/25 pen (EME2)	110°C	140°C (MCHW1, Cl. 930.6)
SMA	40/60 pen	-	100°C
	70/100 pen	-	90°C

When using conventional materials, mix temperatures between 100°C and 140°C are typically seen as favourable temperature range for compaction. At higher temperatures the binder is more fluid and the mixture will not support the weight of the roller, i.e. rollers will simply shove or push the material as opposed to compacting it. It is essential that compaction should be completed before the temperature has dropped to the cessation temperature or minimum rolling temperatures shown in Table 2-2.

The illustration shown in Figure 2-2[10] provides a general summary of how mix temperature relates to the amount of compaction that is required. In the UK, contractors are required to submit a method statement[11] which describes a proposed laying and compaction procedure for each pavement layer. Typically, this statement includes the type and number of rollers; roller passes; and laying and

[9] Huerne H, Dorée A and Miller S (2009). Monitoring hot mix asphalt temperature to improve homogeneity and pavement quality. 6th International Conference on Maintenance and Rehabilitation of Pavements and Technological Control, MAIREPAV 2009.
[10] Bomag (2009). Basic principles of asphalt compaction. BOMAG GmbH, Fayat Group.
[11] Highways England, Transport Scotland, Welsh Assembly Government and the Department for Regional Development Northern Ireland. MCHW, 'Manual of Contract Documents for Highway Works'. Series 900, https://www.standardsforhighways.co.uk/ha/standards/mchw/

compaction temperatures. Information on forming joints is also required, including methods to treat any upstanding edges.

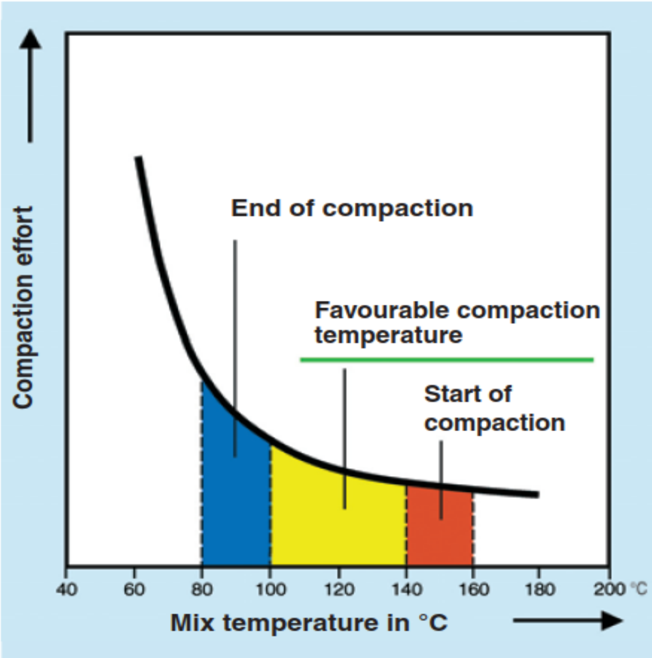


Figure 2-2 - Compaction effort versus temperature (Bomag, 2009)

In order to achieve the specified level of compaction or air voids content, compaction needs to be carried out above a minimum specified rolling temperature. This temperature is mixture dependant and relates to the temperature at which compaction should be substantially completed. As compaction will need to commence above this temperature the contractor needs to take careful allowance of weather conditions which can affect the rate of cooling. The layer thickness has a major influence on the time available for compaction. As such, surface courses present more challenging conditions than materials laid 50 mm or thicker. In particular, wind speed in combination with cool temperatures (wind chill) can dramatically reduce the available time for compaction.

2.3.2. TEMPERATURE DIFFERENCE OR SEGREGATION

Differences in material temperature can lead to differences in the compaction achieved on site. This in hand has the potential to affect the life of the pavement. Differences in temperature occur during the asphalt laying process, as follows:

- Truck transport to site
  - Material hauled to site begins to cool, particularly on the surface of the mix and along the sides of the truck box.
- Paver hopper
  - Material that has cooled along the sides of the truck box is extruded out towards the sides of the paver's hopper when tipped or delivered.
  - The mixture retained in the hopper is run down and the cool material is conveyed to the auger chamber and screeded out.

- As the screed is unable to consolidate the colder mix, areas showing cold material show in the mat. This mechanism works for each load placed and the cyclic nature of the phenomenon becomes apparent[12]. The latter is universally known as end-of-load cooling or segregation.

A Swedish study in 1998[13] used a thermal imaging scanner to measure the surface temperature of material coming out the back of an asphalt paver. The top of Figure 2-3 shows a thermal image of a section of laid surface course and the digital image at the bottom of the figure shows the condition of the surface course after 15 years in service.

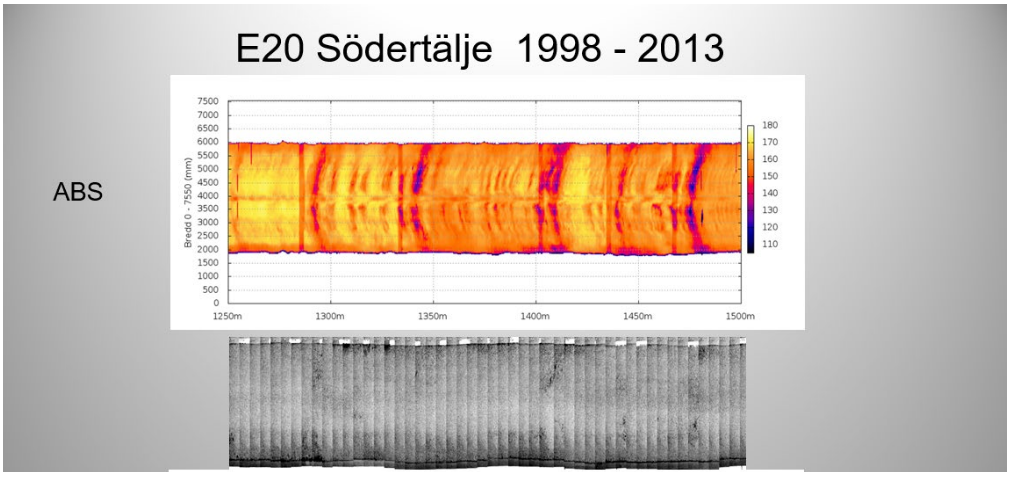


Figure 2-3 - Thermal image versus long-term deterioration (Luby, 2019)

The observed areas of deterioration can be clearly correlated with cold areas which are coloured dark blue. Some of the findings of this work were used in Sweden to improve the insulation and design of asphalt transport trucks.

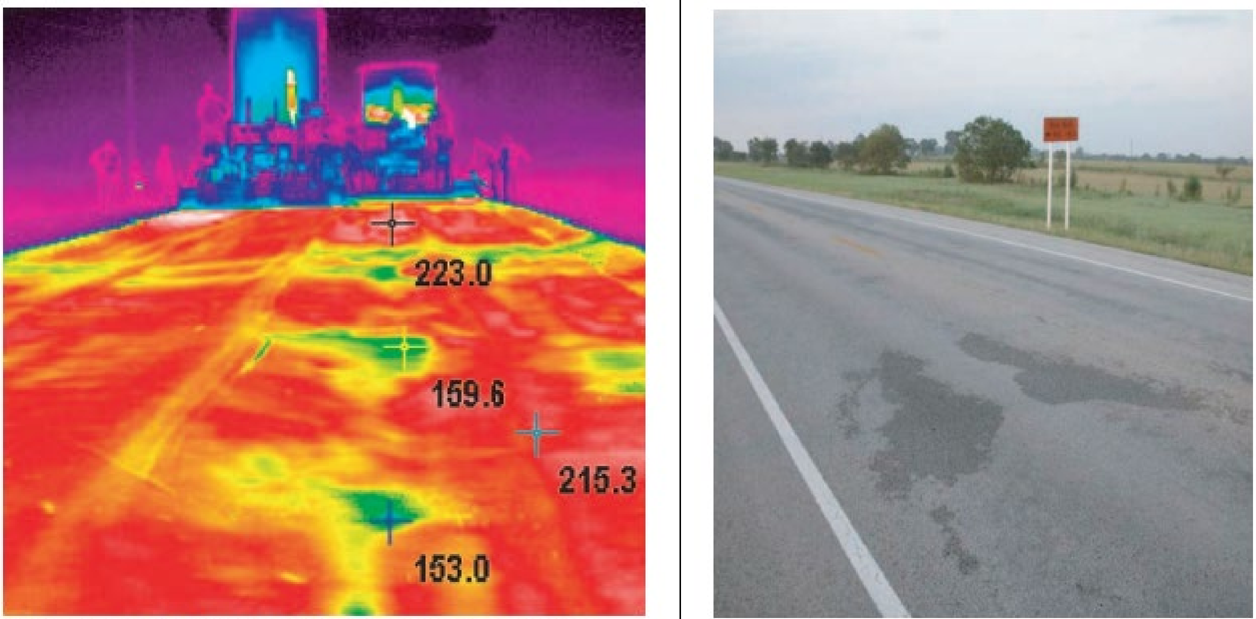
A study carried out in 2000[14] showed that the placement of cooler asphalt can create pavement areas near cessation temperature that tend to resist proper compaction. These areas typically exhibit tearing or roughness or appear to be open textured. Four paving projects were examined to determine the existence and extent of mat temperature differences and associated material characteristics. An infrared camera was used to identify cooler portions of the mat, which were then sampled along with normal-temperature pavement sections. Gradation and asphalt content analysis showed no significant aggregate segregation within the cooler areas. However, these cooler portions of the mat consistently showed higher air voids than the surrounding pavement.

The second Strategic Highway Research Program (SHRP 2)[15] looked at techniques that were able to evaluate temperature uniformity and identify areas of asphalt segregation that do not achieve the

[12] Brock D and Jakob H (1997). Temperature segregation/Temperature Differential Damage. Roadtec Technical Paper T-134.
[13] Luby M (2019). Construction 4.0. 2019 IAT National Conference, Volvo. https://www.instituteofasphalt.org/index.php?id=technicalpresentations
[14] Mahoney J, Muench S and Pierce L (2000). Construction-Related Temperature Differentials in Asphalt Concrete Pavement: Identification and Assessment. TRB Volume: 1712 issue 1.
[15] REPORT S2-R06C-RR-1 (2013). Using Infrared and High-Speed Ground-Penetrating Radar for Uniformity Measurements on New HMA Layers. https://www.nvf-vt.net/uploads/2/1/7/9/21790806/trb-shrp2--r06c.pdf

required level of density. Figure 2-4 shows an infrared thermal image showing cold spots and example of cyclic segregation where cold spot areas in surfacing have low density and hold water after rain events. These areas have an increased risk of early pavement distress such as ravelling and cracking.

Based on the findings of the SHRP 2 report, it was recommended that thermal segregation detection using an infrared bar should be considered for implementation by US road agencies through developing specifications for uniformity assessment.



Photos courtesy of the Washington State Department of Transportation.

Figure 2-4 - Thermal profile (LHS) and visual image (RHS) showing cold spots following rain

2.3.3. COMPACTION EQUIPMENT

Compaction is carried out by the paver and rollers. Asphalt is loaded into the front of the paver which is carried to the rear by a set of conveyor belts, it is then spread out by a set of augers whereupon it is finally levelled and compacted by a vibrating screed. Approximately 75 to 85% of the theoretical maximum density of the asphalt will be obtained when the mix passes out from under the screed[16].

There are three main types of rollers: traditional steel wheel deadweight rollers; steel wheel vibratory rollers; and pneumatic tyre rollers. Vibratory steel wheel rollers offer potential compaction advantages over static steel wheel rollers, but they also require the operator to control more compaction variables and, in certain situations, they must be used with caution, e.g. thin overlays.

The performance of a vibratory roller depends on a complex interaction between the roller operation and the properties of the material being compacted. It is often necessary to carry out comparative

[16] Transportation Research Board (2000). Hot-Mix Asphalt Paving Handbook 2000. Transportation Research Board, National Research Council. Washington, D.C.

trials in which compaction is monitored and optimised, and it is important that operators are properly trained to make best use of vibratory rollers[17]. Operators can turn the vibrations on or off and can also control the vibration frequency and amplitude. In general, higher frequencies and lower roller speeds are preferred because they decrease the distance between surface impacts. For surface courses and mixes rich in bitumen, care should be exercised when using rollers in vibratory mode so that the asphalt binder does not migrate to the surface or that aggregate crushing occurs. In some cases, vibratory mode may be allowed to ensure joint density.

Pneumatic tyre rollers offer a slightly different type of compaction than steel wheel rollers. The arrangement of multiple tyres on both axles serves to both compress and knead the mat, which may or may not be advantageous over steel wheel rollers[18]. Ultimately, the choice of roller is based on preference and experience. Pneumatic rollers are permitted in the UK if they are capable of achieving at least the standard compaction of an 8-tonne deadweight roller.

2.3.3.1. Compaction sequence

The compaction process can be considered to take place in three phases[19]:

- Initial compaction
- Intermediate compaction
- Final compaction

The initial compaction is the first step and will generally produce the highest gain in density of any roller used over the compaction phases. It will produce the majority of the target density in the asphalt layer and should begin at the highest possible temperature that supports the weight of the roller without distorting the mixture. The intermediate phase follows directly after the initial phase with the goal of achieving the final target density or required degree of compaction. The final phase is to remove roller marks and minor surface imperfections.

A clear roller pattern is essential, otherwise the centre of the lane typically receives more roller passes that the outsides. It takes several roller pass over a particular area to achieve satisfactory compaction. Uniform compaction depends on getting the same number of roller passes over each area of the mat. This means that a pattern must be developed that covers the entire mat with an equal number of roller passes from each type of roller. The number of rollers on site is dependent on the daily tonnage being laid. BS 594987 states at least one operational roller at all times; a second roller when daily tonnage exceeds either 100 t of surface course or 150 t of base and binder course; and access to a third roller when daily tonnages exceed 200 t for surface course or 450 t of base and binder courses.

Rolling should normally be carried out in a longitudinal direction, with the driven rolls nearest to the paver. The roller should first compact the asphalt adjacent to any joints and then work from the lower to the upper side of the layer overlapping on successive roller passes. When compacting a longitudinal joint, the first roller pass should be entirely on the hot mat about 0.15m – 0.30m away from the joint. On subsequent passes, the roller should travel mostly on the newly constructed mat

[17] Powell P and Leech D (1983). Compaction of bituminous road materials using vibratory roller. TRRL Laboratory Report 1102. TRRL. Crowthorne: TRL Limited.
[18] Brown E (1984). Experiences of Corps of Engineers in Compaction of Hot Asphalt Mixtures. Placement and Compaction of Asphalt Mixtures, F.T. Wagner, Ed. ASTM Special Technical Publication 829. American Society for Testing and Materials. Philadelphia, PA. pp. 67-79.
[19] EAPA (2017). EAPA position paper: The Ideal Project. https://eapa.org/eapa-position-papers/

and only overlap the older mat by about 0.15m[20]. To achieve uniform compaction, at least half of the roller passes should be along the edges of the layer and the positions at which the roller reverses should be staggered.

Joints in a pavement are typically seen as an area of weakness unless they can be eliminated through echelon paving, also known as hot-to-hot paving. However, the latter requires full lane closure of a carriageway, which is not always possible. The material in the vicinity of a joint is likely to be less well compacted owing to temperature differences in adjacent materials and poor lateral support, i.e. an unconfined edge. Various techniques are available to improve joint density, including joint heaters and edge restraining devices. Additional care needs to be taken at joints to ensure, as far as practical, that they are compacted to a similar level of the main mat.

2.4. INTELLIGENT COMPACTION

Intelligent compaction (IC) originated in the 1970s with a focus on the compaction of soils and can be described as an emerging technology when applied to asphalt materials. It is often difficult to define IC due to manufacturers taking different approaches to the development of the technology concept. A general definition of IC is that it is a system of hardware, software and analysis equipment that are installed on rollers with the purpose of improving the compaction process[21].

The Federal Highway Administration (FHWA) published an extensive study on IC in 2014[22]. The purpose of the study was to answer the question: Can IC measurements be substituted for core data as a basis for acceptance? The study defined IC as vibratory rollers equipped with the following:

- accelerometers mounted on the axle of drums;
- survey-grade global positioning systems (GPS);
- infrared temperature sensors; and
- on-board computers that can display IC measurements as color-coded maps in real time.

IC measurements include an IC measurement value (ICMV – a measure of layer stiffness), roller passes, asphalt surface temperatures, and roller settings including roller vibration frequencies, amplitudes, and speeds.

The scope of the FHWA study included field testing at nine different sites across the USA. The field sites were real construction jobs, owned by state agencies. The selection of field sites was based on the diversity of climate, traffic, and type of construction (overlay and new construction), as well as availability of project windows. Practical feedback from roller operators suggested that IC took the guessing out of their rolling pattern as they no longer needed to remember which utility pole or ground feature they started or stopped at. Similarly, IC technologies were seen to be beneficial under low visibility conditions, such as night operations. Primary conclusions from the study included:

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[20] Roberts F, Kandhal P, Brown E and Kennedy T (1996). Hot Mix Asphalt Materials, Mixture Design, and Construction. National Asphalt Paving Association Education Foundation. Lanham, MD.
[21] Horan R, Chang G, Xu Q and Gallivan, V (2012). Improving Quality Control of Hot Mix Asphalt Paving Using Intelligent Compaction Technology. Transportation Research Record, Journal of the Transportation Research Board.
[22] Chang G, Qinwu X, Rutledge J, and Garber S (2014). A study on intelligent compaction and in-place density. Publication No. FHWA-HIF-14-017.

- IC is very effective for achieving the target level of compaction while at the same time increasing the uniformity of the material.
- The field trial demonstrated that IC rollers could track roller passes, monitor surface temperature, and report an ICMV that the operator could use to better control the compaction process.
- The results showed that a key factor in achieving uniform compaction in the final surface layer was to achieve better compaction uniformity in the underlying layers. This was referred to as the "ground up" approach.
- IC rollers proved to be an effective tool in mapping the surface prior to asphalt so that appropriate corrective measures could be taken to address any soft spots or weak areas.
- IC equipment could be used to develop compaction curves and to determine the optimum number of roller passes.
- Correlation studies showed that ICMVs could be related to in-situ measurements, but there was considerable variability in the correlations.

With respect to the last bullet point, the probable cause of the lack of correlation of asphalt core density data and ICMV was related to mat temperatures during final compaction, which influence the rebound behaviour of the roller drum. It was found that the accelerometers read deeper than the mat layer being compacted which influenced the rebound behaviour of the roller drum. The uncertainties of IC data gridding and GPS precision were also thought to affect the accuracy of data extraction.

To date, the 'jury' still appears to be out on whether IC can be applied to asphalt and the benefits appear to be more related to achieving a uniform coverage by mapping the number of desired passes than any contribution in meeting density. This is because the current IC systems lack the necessary sensitivity to distinguish incremental benefit to improving density in relatively thin asphalt layers.

2.5. AUTOMATED MONITORING SYSTEMS

Automation can be described as the use of technology to deliver a service with minimal human involvement. When applied to asphalt pavements, it typically involves reducing safety risks associated with site operatives, such as minimising exposure to construction traffic and live traffic. Various systems are being developed that monitor the construction phases, including tracking manufactured material from plant to site, recording the laying and compaction operation and measuring pavement layer characteristics. The use of real-time data can also facilitate operational decision making.

A study in Scotland[23] trialled new technologies that enabled remote monitoring during the delivery, laying and compaction process. The systems reviewed included:

- Apex System
  - Software that allows the tracking of delivery vehicles and permits the estimation of waiting times on site.
- Paver IR System
  - Asphalt material temperatures are measured using infrared sensors located on the paver, along with weather and location data. Information can be used to monitor paver movement

[23]Guthrie S (2018). Automatic data collection review – systems and methodology. WSP Report R_70040156_001. WSP 2018.

and identify cold spots (thermal profiles – see Figure 2-3). Information can be uploaded to BIM software and used to produce as-built records.

- Roller System
  - Roller compactor is fitted with an accurate GPS sensor, infrared sensor and an on-board display showing roller passes and temperatures. Similar to the Paver IR system, information can be used for real-time monitoring and incorporation into BIM or asset management systems.

The study recommended some improvements, including changing latitude and longitude data to Ordnance Survey Great Britain (OSGB) to integrate better with BIM and pavement management systems; and the need to develop a clear framework and format for the large amount of data collected in order to assist in the interpretation of data. It was concluded that the systems were considered suitable as quality control (QC) measures, however caution was counselled on using the roller system to demonstrate compliance unless reliable correlations with performance tests, such as density and air voids content, could be determined.

Figure 2-5 and Figure 2-6 provide examples of visual displays from a 2019 surfacing scheme on the A75 in Scotland. Figure 2-5 is based on data collected from a roller system and provides initial rolling temperatures, including how they were distributed during the works. Figure 2-6 shows the number of passes made by a roller on the scheme, including the range of the number of passes covered on different areas of the mat.

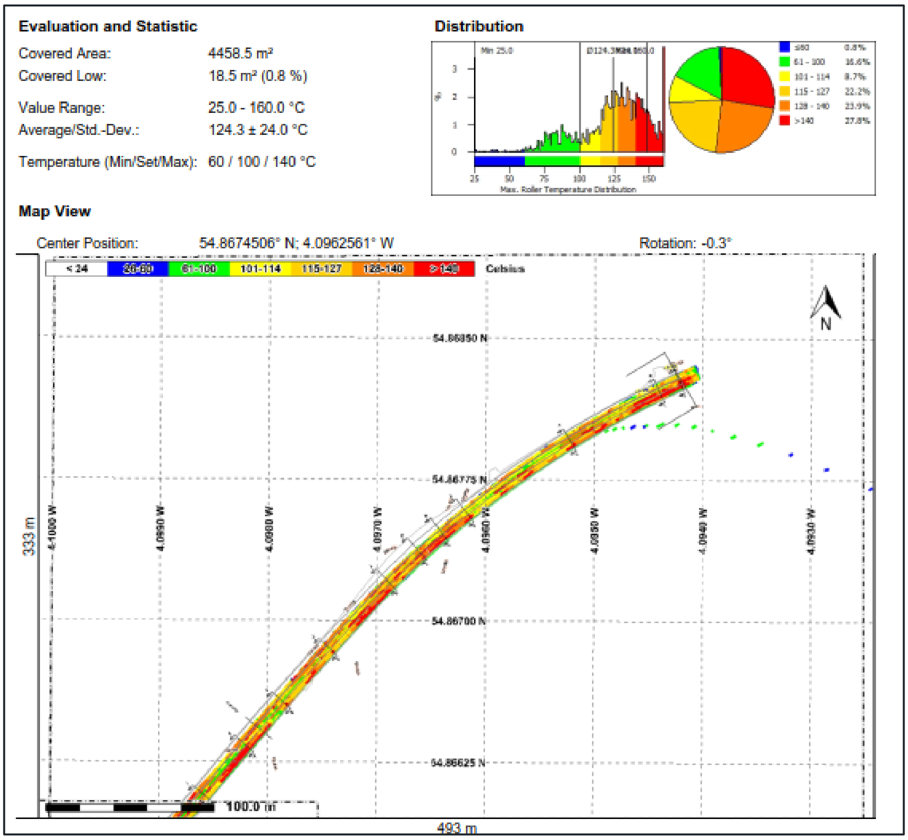


Figure 2-5 - Surface course rolling temperatures (courtesy of HDS)

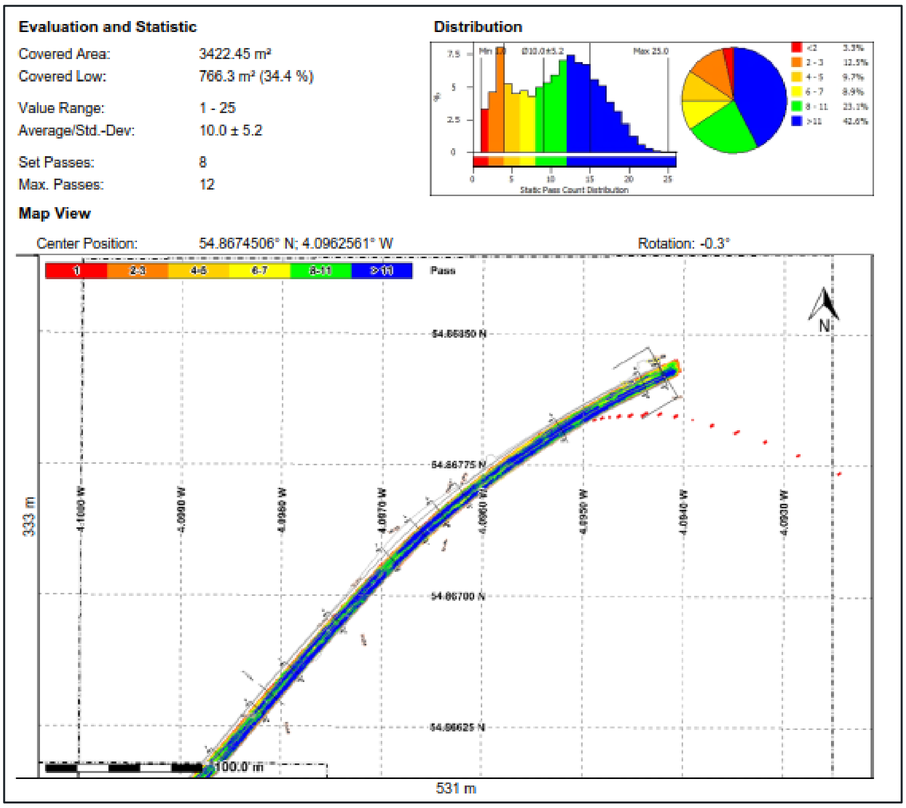


Figure 2-6 - Number of roller passes (Courtesy of HDS)

2.6. EXISTING SPECIFICATIONS

2.6.1. PAVER-MOUNTED THERMAL PROFILING (PMTP)

Paver-mounted thermal profiling (PMTP) is a sensor technology that is mounted on top of a paver to measure the asphalt surface temperature as it leaves the paver screed. The temperature sensors used by PMTP can be either scanning infrared sensors or a thermal camera mounted high up on a paver. Typically, the temperature profiles are divided into 30cm by 30cm grids, where an average surface temperature is reported within each grid. Around a 50m section of temperature profiles is analysed to determine the levels of temperature segregation. PMTP systems can also record paver speeds, stop locations, and stop durations.

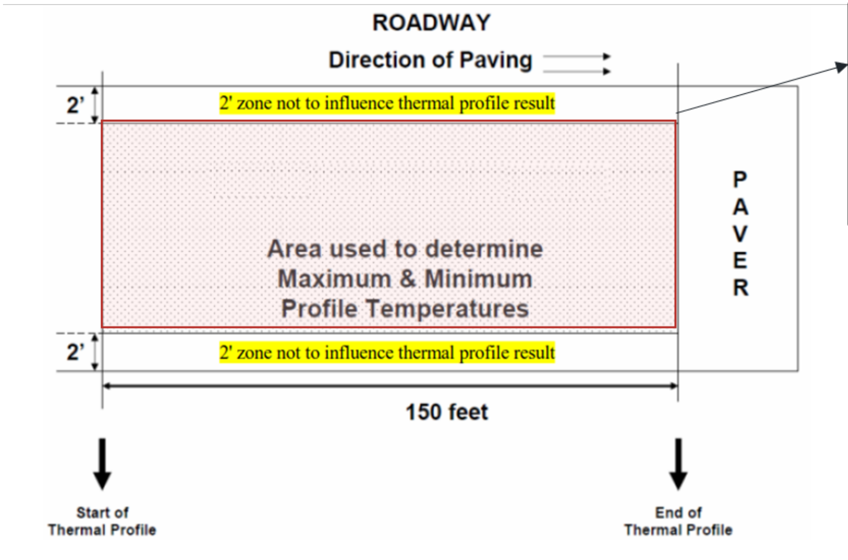
In order to control the quality of construction, the American AASHTO Standard PP80-20[24] recommends a procedure for the continuous thermal profiling of the asphalt mat temperature immediately behind the paver. It describes equipment that uses infrared temperature measurement technology to measure a longitudinal thermal profile across the pavement width directly behind the

[24] AASHTO PP 80-20 (2021). Standard Practice for Continuous Thermal Profile of Asphalt Mixture Construction. American Association of State and Highway Transportation Officials.

paver. Several states in the USA have developed specifications based on the AASHTO standard including Texas[25], Missouri[26] and Minnesota[27].

2.6.2. CALCULATION OF THERMAL SEGREGATION

Figure 2-7 is based on an extract from the Texas Department of transportation procedure mentioned above. It shows what area of the laid mat is used to determine the difference in profile temperatures.



Temp Diff
= Max Temp – Min Temp

Max temp - 98.5 %ile
Min temp - 1 %ile

Temp Diff	Category
TD ≤ 25°F	Low
25°F < TD ≥ 50°F	Moderate
TD > 50°F	Severe

Figure 2-7 - Thermal segregation calculation

Figure 2-7 also shows how the calculated temperature differences are categorised, i.e. low, moderate or severe. In Minnesota and Missouri, monetary price adjustments are used as incentives or disincentives to control the consistency of the mat temperature.

2.6.3. DATA MANAGEMENT AND ANALYSIS SOFTWARE

The three state specifications reviewed all make use of Veta data management and analysis software[28]. The standardised software is used to import and analyse data from construction and testing equipment and the processed data can be viewed as graphs and maps, as shown in Figure 2-8). In particular, the software is produced to provide statistics and histograms to evaluate the uniformity of compaction and surface temperature measurements as part of project quality control operations. PMTP technicians are required to have completed a certified Veta training course within the last 2 years.

[25] Tex-244-F (2015). Test Procedure for thermal profile of hot mix asphalt. https://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit244.pdf
[26] NJSP-18-09B. Paver-Mounted Thermal Profiles. The Missouri Department of Transportation https://spexternal.modot.mo.gov/sites/de/JSP/NJSP1809.doc
[27] Paver mounted thermal profile (PMTP) method. Intelligent compaction, The Transtec Group. https://www.intelligentconstruction.com/downloads/Spec/MNDOT-Thermal-Profile-Spec-2017.pdf

[28] Veta Intelligent Construction. The Transtec Group. https://www.intelligentconstruction.com/veta/

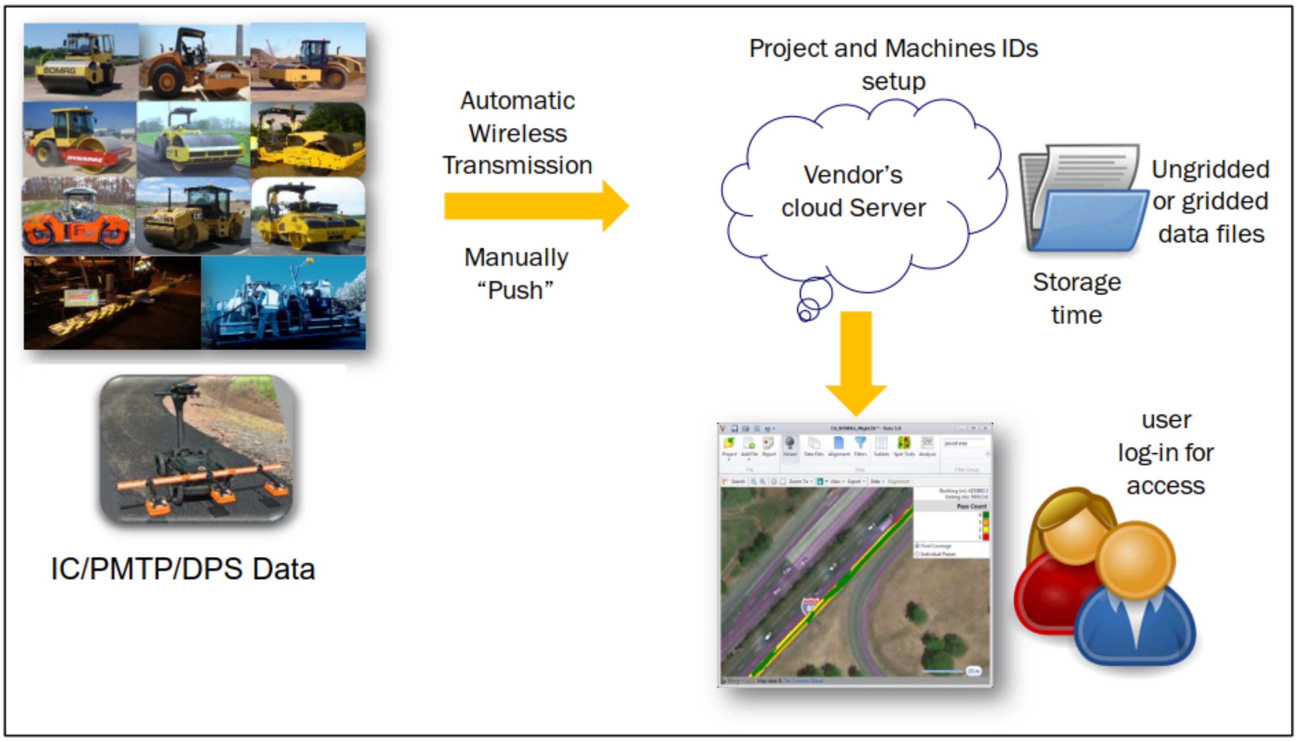


Figure 2-8 - Data collection, data transfer, and data processing (Veta User Guide[29])

Data filters are used within the Veta software to examine the collected information in detail and remove data that is not required or invalid. Filters can be used for machines, pass count, location exclusions, time and temperature. For example, using a minimum temperature filter will remove invalid temperatures from cold edges or operatives standing on the asphalt mat. AASHTO PP80-20 states that surface temperature readings of less than 180 ˚F (80^{0}C) are excluded from the analysis.

The Veta user guide provides examples of how the collected data could be analysed. Figure 2-9 shows two roller temperature maps: the left map shows the first breakdown roller pass; and the right map shows the final coverage temperatures. The first map can be used to view the sublot results for the first breakdown pass for quality control purposes and the second to make sure any specified target pass count was achieved.

[29] Veta User Guide. The Transtec Group https://www.intelligentconstruction.com/wp-content/uploads/2021/08/Veta-7.0-Users-Guide.pdf

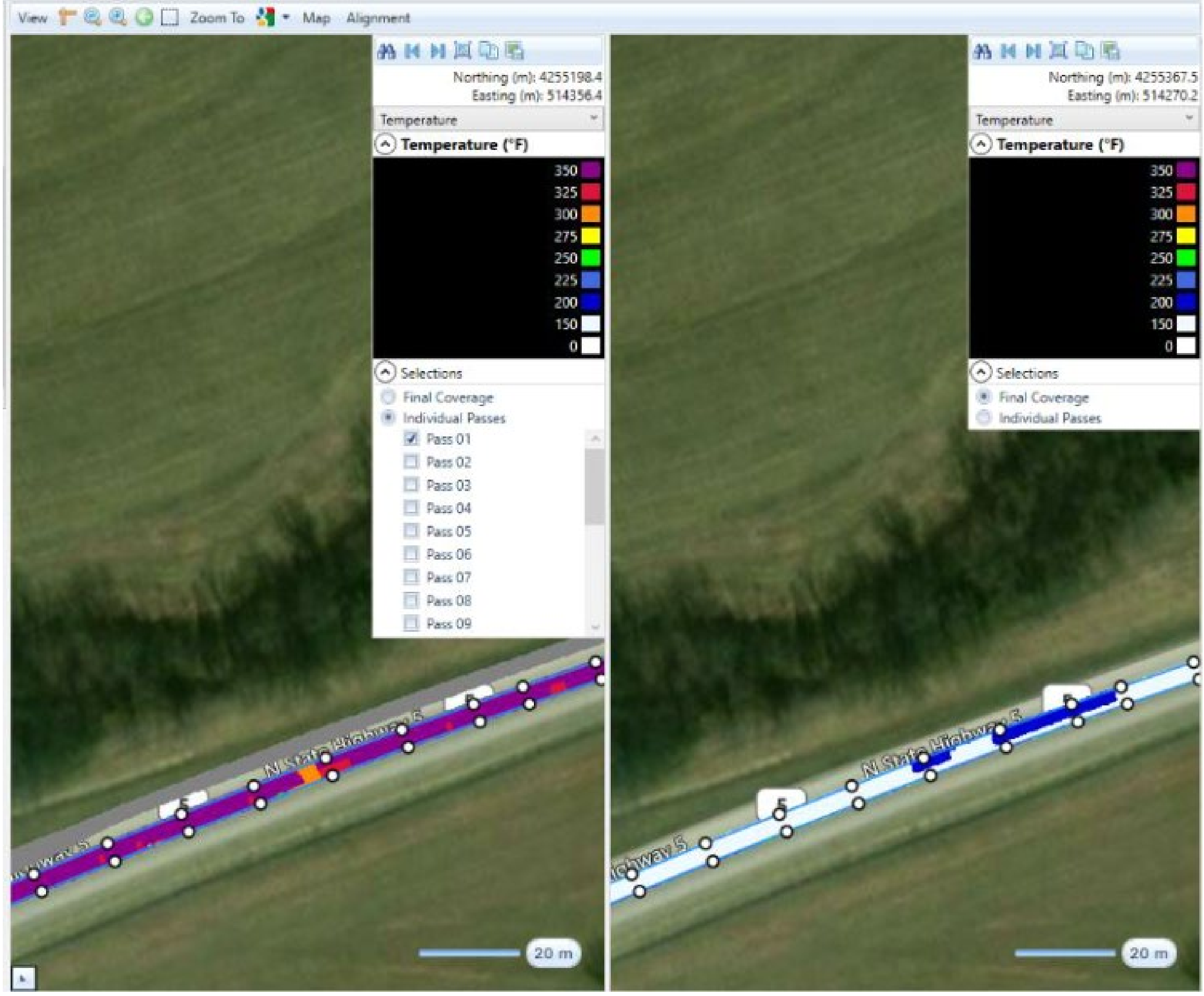


Figure 2-9 - Compactor temperature maps: pass one is shown on the left and final coverage is shown on the right.

3

TRIAL DATA ANALYSIS

3. TRIAL DATA ANALYSIS

As stated in the introduction, trunk road maintenance contracts in Scotland with a value over £250,000 and new build contracts are required to collect and provide electronic data as part of the pavement construction works. A copy of Transport Scotland's Electronic Data Monitoring Requirements are shown in Appendix A.

Taking into consideration the literature review, a recent scheme that collected electronic construction data in accordance with Transport Scotland's requirements was examined. The aim of the exercise was to review how the data is currently collected, processed and presented. The case study was used to identify areas that could benefit from improvement and assist in the preparation of notes for guidance and compliance requirements.

3.1. CASE STUDY - A77 SHORE ROAD, BALLANTRAE

3.1.1. SITE AND DATA COLLECTED

The A77 structural maintenance scheme was around 0.5km long (two lanes) and involved replacing 200mm of surfacing with an inlay that comprised three layers: 30mm TS2010 surface course; 60mm AC20 binder course; and 110mm AC32 base course.

Highway Data Systems (HDS) supplied the following data for this scheme:

- Roller data
  - Roller matrix and data files including date, time, GPS coordinates, temp, direction, and machine ID.
  - Roller Compaction report including map-based displays showing initial rolling temperatures, the number of passes made by a roller on the scheme, and the range (pie chart) of the number of passes covered on different areas of the mat.
- Paver data
  - Feed sensor temperature in auger chamber
  - Vis-IR data: sensor technology on top of a paver which measures the asphalt surface temperature as it leaves the paver screed
- Automated Laying Record Report
  - Movement of HGVs between plant and site and time asphalt was in transport
  - Delivery temperatures and rolling temperatures
  - Air temp, wind speed and rainfall
  - Thermal profile

3.2. DISCUSSION

3.2.1. ROLLER DATA

Figure 3-1 is an extract from HDS's Automated Laying Record dated 16/09/2021. It shows the material delivery and rolling temperatures. It is not clear how these temperatures are calculated but they correspond to data shown in a table within the same report. The table also details the type of material, delivery time, tonnage, time at paver and location of the paver. It is assumed that they represent an average temperature for the load, but it is not clear how they were calculated and how the paver and roller limits were determined. No reference is made to delivery or compaction temperature standards.

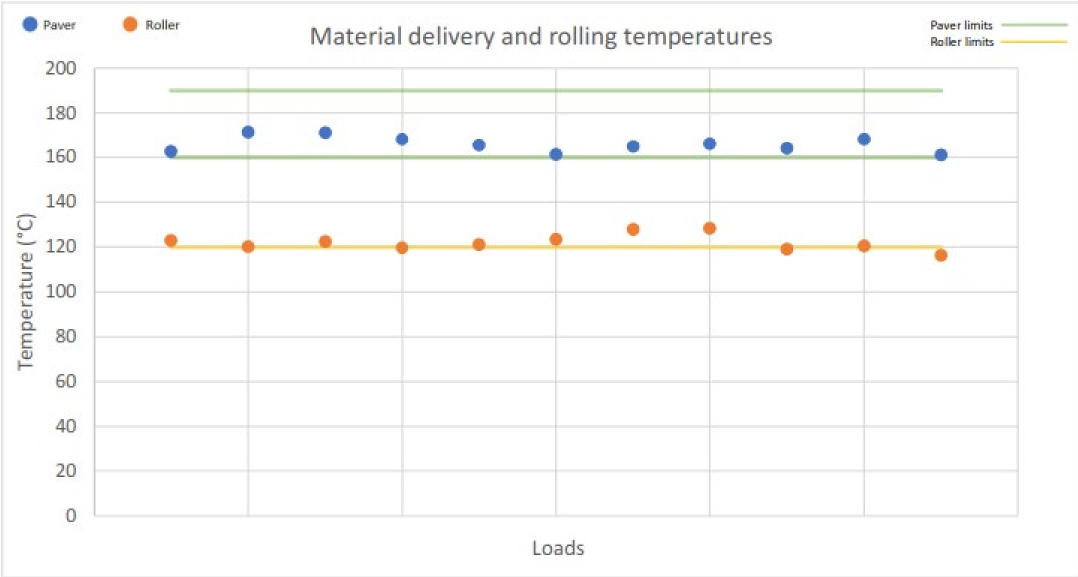


Figure 3-1 - Delivery and rolling temperatures

The Roller Compaction report provides additional information that provides maps that show maximum roller temperature and number of passes made, see Figure 3-2 and Figure 3-3 respectively. These are also accompanied with some statistics including pie charts and histograms.

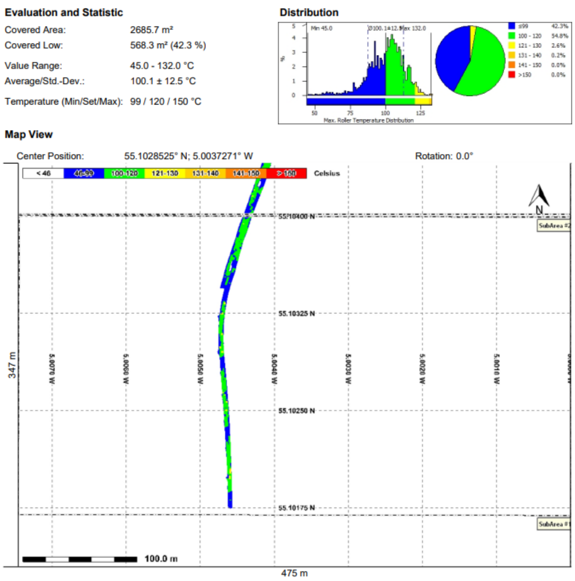


Figure 3-2 - Maximum roller temperature

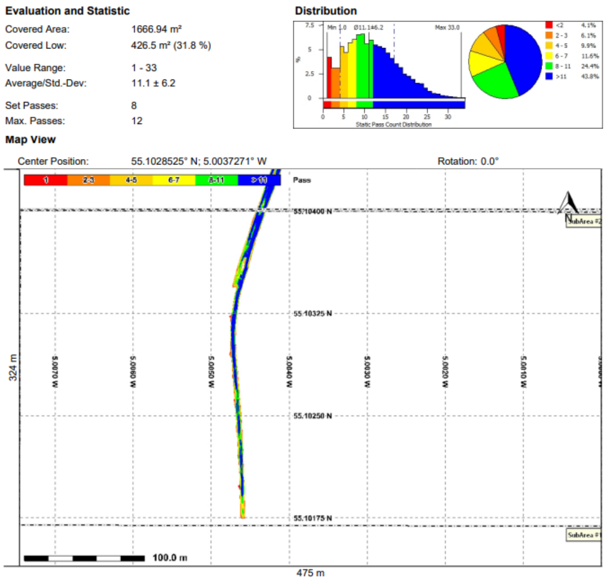


Figure 3-3 - Roller passes

From the literature review it appears that the breakdown temperature (first pass) is one of the key measurements that should be reported and displayed and this appears to be shown in Figure 3-2.

However, the minimum value will be material and binder specific and this should be reflected in the pie charts and histograms. It is equally important that all areas of the mat receive at least several passes. It is important to recognise that once the material has cooled below a certain level, any subsequent passes will not improve compaction levels. The latter is discussed further in the next section.

3.2.2. PAVER DATA INCLUDING THERMAL PROFILE

Figure 3-1 shows paver temperature data and the numbers correspond to the table in the Automated Laying Record dated 16/09/2021. An examination of the raw feed sensor data showed that only one of the three sensors was recording. It is unclear how the temperatures reported were calculated, but appear to be based on delivered loads.

The Vis-IR data which measures the asphalt surface temperature as it leaves the paver screed was used to produce the thermal profile shown in Figure 3-4. The thermal map, paver stop and profile data is shown for the entire scheme (900m). It is not clear how helpful or relevant some of this data is in its current form and it is suggested that summary data should be reported based on individual loads or a short linear length, e.g. 45-50m. Some of the summarised profile data results appear to be similar in nature to the PMTP specifications reviewed under section 2.6 of this report. However, there are differences in the criteria stated and, from an initial analysis of the raw data files, they do not seem to be calculated as per the PMTP calculation methods outlined in the specifications reviewed.

Figure 3-4 - Thermal profile

4

DRAFT NOTES FOR GUIDANCE

4. DRAFT NOTES FOR GUIDANCE

Based on the literature and case study review, draft Notes for Guidance (NG) on Transport Scotland's electronic data capture requirements (see Appendix A) have been prepared. The NG Clauses directly relate to, and should be read in conjunction with, the Specification Clauses given in Appendix A. It should be noted that not all Specification Clauses have corresponding NG Clauses.

Notes for Guidance - Transport Scotland Electronic Data Monitoring Requirements

Scope

1 The purpose of this clause is to define the requirements for the use of electronic data capture during resurfacing works for quality control and as-built record purposes.

2 Sub-clause 5 details the requirements for ensuring that sites chainages and GPS coordinates are linked with each other. It is important that these provide an accurate representation of the site layout and that the data can be imported and analysed.

3 Some of the following Sub-Clauses provide general guidance on how data should be collected, analysed and presented in order to meet draft compaction compliance requirements that are under development. [See Section 5 of this report]

Equipment Requirements

4 Sub-Clause 9 requires a qualified representative for on-site technical assistance. Individuals performing daily setup of the equipment shall be properly trained.

Asphalt Transportation

5 Sub-clause 12 and 13 outline electronic report requirements associated with the tracking and delivery of asphalt to the site. In addition to the information required, the layer type (surface, binder or base) and nominal target depth shall be recorded.

Paver Digital Technology

6 In addition to the electronic laying requirement detailed in Sub-clause 13, the information reported shall include:

(i) Weather charts that are updated every 30 minutes.

(ii) A graph of paver stop time versus chainage. The latter should be available as GPS Lat/Long (WGS84). It is important that individual loads, material types and their respective chainage are recorded and can be clearly identified.

7 Sub-Clause 14 requires that each load of bituminous material shall be checked for temperature compliance at the point of discharge into the paver. Average load temperatures shall comply with BS 594987, which specifies minimum delivery temperatures for recipe AC, HRA and SMA mixtures. It also lays down minimum rolling temperatures for designed AC dense, heavy-duty and high-modulus binder course and base (including EME2) at which compaction should be substantially complete. As part of reporting delivery temperatures these temperatures shall be used as an indicator of compliance.

8 Sub-Clause 19 requires data to be collected and analysed to report the percentage area of cold spots which fall below the specified minimum laying temperature as detailed in MCHW series

900. It is important that a thermal plot is produced for each 50m section laid as an individual layer and that the chainage is clearly shown. [Further guidance on how collected data should be analysed and presented is provided under Section 5 of this report].

Roller Digital Technology

12 Sub-Clause 21 requires that the roller's onboard temperature sensor captures the first pass temperature, GPS and pass count data. The first pass shall be completed within 20 minutes of the base and binder course being laid, and 5 minutes after the surface course has been laid.

13 Sub-Clause 26 specifies that the roller data shall be provided as a geospatial colour coded shape file that includes information on the first pass temperature and % coverage. It is recommended that 85% of the mat shall receive a minimum of 6 passes and this criteria shall be used to demonstrate compliance in reporting. The first pass temperature shall be reported and be within 10℃ of the stated temperatures in BS 594987 minimum mixture temperature immediately prior to rolling. A summary of the location of first pass temperature and total number of passes made on each area of the mat shall be provided in the form of a geospatial colour coded shape file.

5

COMPACTION COMPLIANCE FRAMEWORK USING ELECTRONIC DATA

5. COMPACTION COMPLIANCE FRAMEWORK USING ELECTRONIC DATA

5.1. ACHIEVING ADEQUATE COMPACTION

As stated previously, the primary objective of this study is to use real-time electronic data to monitor the laying and compaction of asphalt material to ensure it has been properly compacted. Clear benefits include improved material durability and a possible end to traditional compliance testing which is labour intensive, destructive and potentially dangerous.

This section outlines electronic data requirements that are considered to demonstrate that adequate compaction has been achieved. It is proposed that if a laying contractor can demonstrate a range of criteria, then traditional compaction monitoring as described in Series 900, e.g. coring and indirect density gauge readings, would not be required.

5.2. REQUIRED COMPACTION CRITERIA

The following compaction criteria forms part of a process control procedure that will ensure that a target compaction has been achieved.

5.2.1. DELIVERY TEMPERATURE

Using infrared sensors located on the paver, recorded asphalt material temperatures shall be used to calculate the average temperature per load. Average load temperatures shall comply with BS 594987, which specifies the minimum delivery temperature.

5.2.2. TEMPERATURE PROFILE

5.2.2.1. Apparatus – Thermal camera or thermal imaging system

A Paver-Mounted Thermal Profile (PMTP) system shall be used to continually monitor the surface temperature of the asphalt mat. This shall be carried out during paving operations in order to determine the temperature difference levels for each 50m length delivered to the site. The PMPT shall consist of a thermal imaging system that meets the following requirements:

(i) Longitudinal and lateral surface temperatures at spacings ≤ 300mm at all paving speeds with a tolerance ± 25mm.

(ii) Infrared sensors to measure from 0°C to 250°C with an accuracy ± 2°C or ± 2.0% senser reading, whichever is greater.

(iii) Profiling the pavement width, up to 3.6m wide.

5.2.2.2. Use of system

The PMTP system shall be used to obtain a maximum baseline and minimum temperature for each 50m Length of material delivered to site. This shall be carried out by analysing the temperature readings from the area shown in Figure 5-1. The PMTP data should be configured to record pavement temperatures within a grid that is no more than 300mm x 300mm. It is important that the temperatures and their locations (GPS coordinates) are recorded so that areas with large temperature differences can be recorded and identified. Surface temperature readings within 500mm of the edge of the compacted mat shall not be used to calculate the thermal profile. Similarly, surface temperatures readings less than 70°C shall be excluded from the calculations.

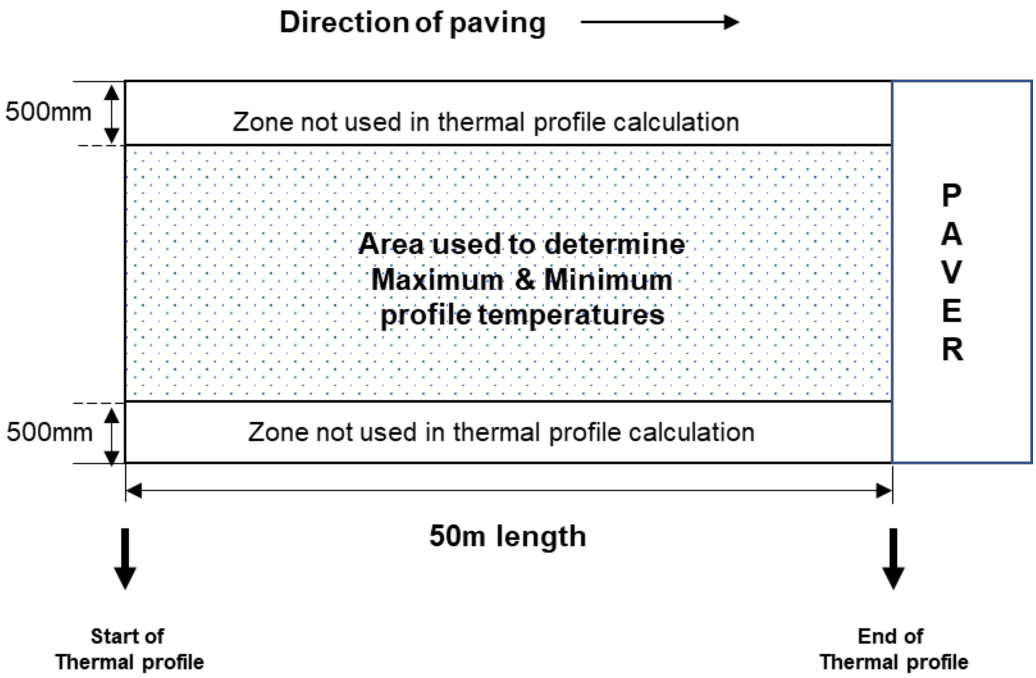


Figure 5-1 - Thermal profile area

5.2.2.3. Calculation of temperature difference

The temperature difference or range, reported to one decimal place, shall be reported for each 50m length using the following equation:

Temperature Difference (TD) = T_{max} - T_{min}

Where: T_{max} = surface temperature reading at the 98.5 percentile (°C) and

T_{min} = surface temperature reading at the 1 percentile (°C).

5.2.2.4. Temperature difference category

The surface temperature readings for each 50 length shall be categorised in accordance with the ranges specified in Table 5-1.

Table 5-1 - TD Category

Temperature Difference – 50m	
TD	**Category**
TD ≤ 15°C	Low
15°C < TD ≤ 30°C	Moderate
TD > 30.1°C	Severe

The reported temperature category for each load shall be reported and be Low or Moderate.

5.2.3. PAVER STOPS

Excessive paver stops will result in the material cooling and require a new construction joint to be formed. The excessive cooling of asphalt is material specific and a paver stop shall be defined as greater than 20 minutes for base and binder courses, and greater than 5 minutes for surface course materials. A graph showing paver stop time versus chainage is required and it is important that individual loads and material types are recorded.

5.2.4. ROLLER COMPACTOR

5.2.4.1. Maximum time prior to first pass

The first pass of the roller shall be completed within 20 minutes of the base and binder course being laid, and 5 minutes after the surface course has been laid. If this criteria is not met then a new construction joint must be formed.

5.2.4.2. Temperature at first pass

The roller compactor infrared sensor shall be used to record the first pass temperature. This shall comply with the recommended BS 594987 minimum mixture temperature immediately prior to rolling.

5.2.4.3. Roller passes and mat coverage

GPS sensors fitted to the roller compactor(s) shall be used to demonstrate that 85% of the laid mat receives a minimum of 6 passes.

5.3. SUMMARY OF COMPACTION COMPLIANCE CRITERIA

Table 5-2 summarises the electronic data required to demonstrate that the compaction process has been carried out to an acceptable standard.

Table 5-2 – Compaction compliance

Process	Measurement	Compliance criteria
Delivery temperature	Average temperature per load	BS 594987 - minimum delivery temperature
Temperature profile	Temperature Difference (TD)	Low or Moderate Category
Paver stops	Time stopped	≤ 20 min for base and binder courses ≤ 5 min for surface course
Roller compactor	Time prior to first pass	≤ 20 min for base and binder courses ≤ 5 min for surface course
	Temperature at first pass	BS 594987 – within 10 ℃ of the minimum mixture temperature immediately prior to rolling
	Passes & percentage coverage	≥ 6 passes with 85% coverage

6

RECOMMENDED NEXT STAGE

6. RECOMMENDED NEXT STAGE

6.1. IMPROVING THE QUALITY OF CONSTRUCTION

From the international literature review, a good PMTP appears to be one of the most critical factors in achieving the desired compaction level. If materials are delivered at the recommended delivery temperatures (BS 594987) and temperature differences in the asphalt as it leaves the paver screed are minimised, then there is a high likelihood that good compaction will be achieved following the initial passes made by the roller.

6.2. PILOT TRIALS

The draft Notes for Guidance and compliance requirements presented in Section 4 and 5 adopt a similar approach to that being used in the USA. However, certain aspects have been adapted for the type of materials and equipment available in Scotland.

The next stage of the project should be to apply the new guidance and compliance requirements to forthcoming schemes to determine whether the data collection and processing requirements are practical and achievable. It is recommended that the results and feedback on these trials be shared and reviewed with the TSPF Automated Data Capture subgroup to determine whether further amendments are required.

Appendix A

ELECTRONIC DATA REQUIREMENTS

Transport Scotland Electronic Data Monitoring Requirements*

Scope

1 This specification sets out the requirements for the use of electronic data capture during resurfacing works for quality control and as-built records purposes. Proper compaction is key to the durability of asphalt roads and digital technology has the ability to improve the way roads are constructed.

2 These requirements are intended to be used throughout all stages of the construction process; asphalt transportation, paving operation, compaction and processing of data.

3 All tasks are the contractor's responsibility, unless designated otherwise.

4 All tests shall comply with the requirements of the DMRB, SHW or this document. Any other methodology will not be accepted.

5 The contractor is responsible for ensuring all reported chainage and GPS locations are accurately positioned and correlated with each other and are an accurate representation of the construction site layout.

Equipment Requirements

6 The contractor shall ensure that the equipment holds built-in provisions to facilitate the calibration and verification of the test results.

7 The Contractor shall supply proof of calibration of the equipment. The equipment shall be calibrated at intervals not exceeding 12 months in conjunction with a calibration protocol and / or the manufactures recommendations. Evidence of recent conformity and / or consistency check may be requested during the period of the contract.

8 The Contractor must provide all plant, equipment, staff, licenses, administration and software (including firmware and software updates) with appropriate licenses to complete the works and ensure that all their apparatus is in good working order throughout the period of the contract.

9 A qualified representative for on-site technical assistance should be provided during the project to maintain equipment within specifications and requirements.

Asphalt Transportation

10 Live tracking of asphalt delivery vehicles shall be available to the paving crew via a secure web portal.

11 The tracking information shall include, as a minimum, an identification number for the delivery vehicles, record of the plant supplying the material, full designation of asphalt mix, departure time from the plant, expected arrival time on site and weight of load.

12 Location details of where the asphalt is deposited shall also be recorded using both the linear chainage system and GPS Lat/Long (WGS84) . An electronic report detailing all the above information shall be available following the construction process.

* Minor differences in wording exist between Clause 976AR and Clause 977AR. The former clause is used in maintenance contracts and the latter for new build contracts. However, the core requirements remain the same in both Clauses.

Paver Digital Technology

13 Paver technology shall capture a full electronic laying record including; ambient weather conditions at the time of laying and as a minimum the following for each load: supplying plant, material, load temperature, start/end location, road layer (base, binder or surface), thickness and date/time laid. Any stoppages shall be easily identifiable by generation of a graph of paver stop time versus chainage.

14 Each load of bituminous material shall be checked for temperature compliance at the point of discharge into the paver.

15 A record of the discharge location shall be taken using both GPS Lat/Long (WGS84) and the site linear chainage system.

16 GPS tracking of the paver shall be available to an accuracy to within 1m, and with the ability to identify any stoppages.

17 Continuous temperature scans of the full width of the material being laid immediately after the rear screed of the paver shall also be recorded. Surfacing operatives shall take care not to obstruct the temperature scan.

18 A minimum 95% availability of data capture shall be achieved.

19 Data must be provided to the Overseeing Organisation as a geospatial colour coded shape file incorporating captured metadata. This report shall generate details of % area of cold spots below the specified minimum laying temperature as detailed in MCHW series 900.

Roller Digital Technology

20 The contractor shall supply sufficient numbers of rollers, and other associated equipment, necessary to complete the compaction requirements for the specific materials.

21 Roller technology must capture first pass temperature and pass count data for the full lane area for the compacted mat.

22 The system must be capable of producing a single combined compaction record where multiple rollers are used in tandem.

23 The system shall include an in-cab display to aid roller drivers with effective compaction. This should include details of any cold areas identified by the continuous temperature scans being carried out on the paver.

24 GPS accuracy is required to within 20cm

25 A minimum 95% availability of data capture shall be achieved.

26 Data must be provided to the Overseeing Organisation as a geospatial colour coded shape file incorporating captured metadata. This will include:

A) Data on % coverage of material below the specified minimum rolling temperature at first pass of the roller and

B) Data on % coverage with each number of roller passes.

Processing of Data

27 Data must be provided to the Overseeing Organisation as a compiled laying record in a format that allows the copy and transfer the data with ease such as CSV, Excel spread sheet or unlocked PDF.

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