Sub-Task 2: Evaluation of QC and QA Test Methods

Final

Highways England, Mineral Products Association and Eurobitume UK

Project reference: Task 1-444 Collaborative Research
Project number: 60559099

4 March 2019

highways england | mpa essential materials sustainable solutions | eurobitume UK

Quality information

Prepared by	Checked by	Verified by	Approved by
Giacomo D'Angelo	Yi Xu	Ayad Subhy Joanne Edwards	Daru Widyatmoko
Dr Giacomo D'Angelo Pavement Engineer	Dr Yi Xu Pavement and Materials Engineer	Dr Ayad Subhy Pavement and Materials Engineer Dr Joanne Edwards Associate Director	Dr Daru Widyatmoko Technical Director

Revision History

Revision	Revision date	Details	Authorized	Name	Position
01	June 2018	Comments incorporated			
02	February 2019	Comments incorporated			

Distribution List

# Hard Copies	PDF Required	Association / Company Name

Prepared for:

Highways England, Mineral Products Association and Eurobitume UK

Prepared by:

Dr Giacomo D'Angelo
Pavement Engineer

AECOM Infrastructure & Environment UK Limited
12 Regan Way
Chetwynd Business Park
Nottingham NG9 6RZ
United Kingdom

T: +44 (115) 907 7000
aecom.com

Table of Contents

Executive summary 1
1. Scope 1
2. Methodology 2
2.1 Evaluation of conventional QC/QA test methods 2
2.4 Validation trials 3
2.5 Setting of acceptance criteria for QA 3
3. Review of existing and innovative technologies 5
3.1 Surface regularity 5
3.2 Surface macro-texture 10
3.3 In-situ density 14
3.4 Intelligent compaction 17
3.5 Pavement distresses 19
3.6 Asphalt temperature 23
3.7 Selection of innovative technologies 25
4. Laser based system to measure surface regularity 26
4.1 Introduction 26
4.2 Data analysis 27
4.3 Compliance results 28
4.4 Repeatability test 29
4.5 Summary of findings 31
5. Laser based system to measure surface macro-texture 32
5.1 Introduction 32
5.2 Data analysis 33
5.3 Compliance results 36
5.4 Repeatability test 36
5.5 Summary of findings 36
6. Contactless system to measure in-situ density 38
6.1 Introduction 38
6.2 Mode of operation 39
6.3 Feedback from trials (US and UK) 41
6.4 Summary of findings 42
7. Automated quality monitoring systems 43
7.1 Introduction 43
7.2 APEX System 43
7.3 PAVE-IR Scanner System 46
7.4 Roller System 48
7.5 Asset Management System (data collection at construction stage) 52
7.6 Summary of Findings 52
8. Discussion and Conclusions 54
9. Recommendations for future work 56
Acknowledgements 57
References 58
Appendix A – LSE v. RSE comparative study 67
Appendix B – 3D-TD v. Volumetric Patch comparative study 75

Figures

Figure 1 – Intelligent Compaction System (courtesy Aggregate Industries)... 17
Figure 2 – Vehicle mounted Laser Straight Edge system (courtesy of MATtest Ltd) 26
Figure 3 – MATtest LSE repeatability trial results 29
Figure 4 – MATtest vehicle mounted 3D-TD system (courtesy of MATtest Ltd). 32
Figure 5 – Example of 3D texture road profile built via MATtest software program [136]. 33
Figure 6 – Summary of 3D-TD v. Volumetric Patch measurements 34
Figure 7 – Influence of aggregate size on the percentage Difference between 3D-TD and Volumetric Patch measurements 35
Figure 8 – MATtest 3D-TD repeatability trial results 36
Figure 9 – Side view of PaveScan cart [141] 39
Figure 10 – (a, b, c) Calibration of PaveScan prior testing; (d) Recommended survey layout; (e) Core calibration [91] 40
Figure 11 – PaveScan v. PQI density 41
Figure 12 - Screenshot of the APEX Interface [146] 44
Figure 13 – Example of APEX Load Location Map 45
Figure 14 – Examples of APEX Graphs 45
Figure 15 Example of PAVE-IR Thermal Profile. 47
Figure 16 Example of PAVE-IR Temperature Plot. 47
Figure 17 Example of PAVE-IR Paver Stops 47
Figure 18 - Screenshot of typical Roller Analysis Software [146] 48
Figure 19 – Example of Roller Static Passes.. 49
Figure 20 – Example of Maximum Rolling Temperature 50
Figure 21 – Example of Maximum Rolling Temperature – Cool Material 51
Figure 22 Horizons – Example of Roller Passes 52
Figure 23 – LSE vs RSE number of surface irregularities above 4 mm 72
Figure 24 – LSE vs RSE number of surface irregularities above 7 mm 73
Figure 25 – LSE vs RSE number of surface irregularities above 10 mm 74
Figure 26 –3D-TD vs Volumetric Patch measurements per each location... 81

Tables

Table 1: Summary of Stages....2
Table 2: Assessment Procedure for 'Innovative' Techniques and Materials (adapted from Highways England) [1]. 3
Table 3: Surface regularity detection methods....7
Table 4: Surface macro-texture measurement systems....12
Table 5: Asphalt in-situ density measurement systems....15
Table 6: Intelligent compaction – automatic feedback system capable of varying compactive effort based on measured stiffness....18
Table 7: Pavement distresses detection systems....21
Table 8: Asphalt temperature measurement systems....24
Table 9: MCHW 1 Clause 702 Table 7/2 Maximum Permitted Number of Surface irregularities [9]....28
Table 10: Compliance results....28
Table 11: Total number of irregularities above 4 mm, 7 mm, and 10 mm recorded along the section for each run30
Table 12: Percentage Difference between 3D-TD and Volumetric Patch, together with variations of Volumetric Patch....35
Table 13: Available Automated Systems Datasets....43
Table 14: LSE v. RSE – M1 J5....67
Table 15: LSE v. RSE – M25 J25....67
Table 16: LSE v. RSE – M25 J28....67
Table 17: LSE v. RSE – M25 J23....67
Table 18: LSE v. RSE – M4 J4....68
Table 19: LSE v. RSE – M4 J4 Heathrow Spur Road....68
Table 20: LSE v. RSE – A76 North of Garleffan....68
Table 21: LSE v. RSE – A82 Garshake Road....69
Table 22: LSE v. RSE – M8 Arkleston....69
Table 23: LSE v. RSE – M1 J16-J19....69
Table 24: LSE v. RSE – A269 Ninfield Road....71
Table 25: LSE v. RSE – A46 Hobby Horse to Widmerpool....71
Table 26: 3D-TD vs Volumetric Patch – M1 J5....75
Table 27: 3D-TD vs Volumetric Patch – M25 J25....75
Table 28: 3D-TD vs Volumetric Patch – M25 J28....76
Table 29: 3D-TD vs Volumetric Patch – M25 J23....76
Table 30: 3D-TD vs Volumetric Patch – M4 J4....77
Table 31: 3D-TD vs Volumetric Patch – M4 J4 Heathrow Spur Road....77
Table 32: 3D-TD vs Volumetric Patch – A76 North of Garleffan....77
Table 33: 3D-TD vs Volumetric Patch – A82 Garshake Road....78
Table 34: 3D-TD vs Volumetric Patch – M8 Arkleston....78
Table 35: 3D-TD vs Volumetric Patch – M1 J16-J19....79
Table 36: 3D-TD vs Volumetric Patch – A269 Ninfield Road....80
Table 37: 3D-TD vs Volumetric Patch – A46 Hobby Horse to Widmerpool....80

Executive summary

In November 2017, Arup AECOM Consortium was commissioned by Highways England (HE), Mineral Products Association (MPA) and Eurobitume UK to conduct works under the Collaborative Research Project. This project includes three sub-tasks and this report details the work undertaken under Sub-Task 2: Evaluation of QC and QA Test Methods.

Sub-Task 2 explored the possibility of incorporating recent technological advancements and automation in quality monitoring equipment, as an alternative to the conventional testing and monitoring of asphalt pavements. A driver for this review is that the conventional test methods inherently carry safety risks for site technicians who undertake the works. The use of automated technologies currently available to the construction industry could remove and/or mitigate the exposure of site technicians.

The areas considered within this report are: asphalt surface regularity, asphalt surface macro-texture, asphalt in-situ density, intelligent compaction, asphalt pavement distress and asphalt temperature.

A literature review of conventional and innovative technologies was completed along with engagement with industry suppliers and manufacturers.

Innovative technologies were selected for further assessment based on automation level, measurement speed, experience on the Strategic Road Network (SRN) and availability in the UK. The relevant suppliers for the selected technologies were engaged and site trials were planned to assess the selected technologies against conventional methods through validation trials.

The innovative technologies/systems identified for further analysis are the Laser Straight Edge (LSE, measuring surface regularity), the 3D-TD (measuring texture depth), the PaveScan (measuring in-situ density), the APEX system (optimising efficiency of paving process), PAVE-IR (system producing laying records) and roller system (intelligent compaction system).

The 3D-TD system and LSE can monitor the entire site at traffic speed and measurements are carried out continuously and stored digitally. These outputs can be combined with other information from site and incorporated into Building Information Modelling (BIM) or Pavement Management Systems (PMS).

Overall, based on the data analysed, the automated LSE approximates to Rolling Straight Edge (RSE), although more work is recommended to build up the evidence base for any future change to the contractual base line of the RSE. Limited repeatability testing of the LSE was undertaken which supports that, with standardisation, it could be a suitable alternative to the RSE.

Results analysed show that 3D-TD has a relatively good repeatability and a good correlation with volumetric patch (higher than 94%). The relative difference between the two methods was lower than the volumetric patch variation from randomly selected locations within a nominally homogeneous pavement section reported in BS EN 13036-1 (27%). Therefore, on the basis of this work it is considered that 3D-TD approximates to the volumetric patch.

Reproducibility trials would be needed to confirm the current findings for both the LSE and 3D-TD to have increased confidence in using the new innovative systems for quality control (QC) and quality assurance (QA) purposes.

PaveScan is one of a number of techniques proposed as an alternative method of measuring in-situ density. These systems may be adapted to use on a vehicle; therefore, they have the potential to increase survey safety and automation. However, this review found large variations in this system when compared against other methods such as core density and Pavement Quality Indicator (PQI). Therefore, further research is needed to demonstrate the suitability of this system for QC/QA.

The automated APEX, PAVE-IR and Roller systems provide continuous streams of large datasets automatically captured during the construction. The real-time monitoring can facilitate operational decisions. The comprehensive information also helps in the follow-up investigations for any non-compliance cause identification and/or prevention purposes. Overall, these systems are considered suitable as QC measures to improve construction quality and efficiency.

Overall, the study has yielded further understanding of how innovative technologies can assist in increasing the automation level of conventional QC and QA test methods. The adoption of similar technologies may result in a safer and more efficient quality management process. The research has provided a foundation for further development of the assessed technologies and future revision of specification requirements.

1. Scope

In November 2017, Arup AECOM Consortium was commissioned by Highways England (HE), Mineral Products Association (MPA) and Eurobitume UK to conduct works under the Collaborative Research Project. This overarching project includes three sub-tasks:

- Sub-Task 1: Ensure that asphalt surfacings continue to deliver value for money on the SRN and to maximise the benefit from innovation
- Sub-Task 2: Evaluation of QC and QA test methods
- Sub-Task 3: Low Temperature Asphalt / Warm Mix Asphalt evaluation

Sub-Task 1 and Sub-Task 3 are reported separately.

This report details the work undertaken under Sub-Task 2. The aim is to explore the possibility of incorporating recent technological advancements and automation in quality monitoring equipment, as an alternative to the current quality control (QC) and quality assurance (QA) testing of asphalt pavement in situ. According to ISO 9000:2015 definitions: QC is the part of quality management focused on fulfilling quality requirement; QA is the part of quality management focused on providing confidence that quality requirement will be fulfilled.

The areas being considered are: asphalt surface regularity, asphalt surface macro-texture, asphalt in-situ density, intelligent compaction, asphalt pavement distress and asphalt temperature. Most of the conventional test methods used to measure and/or monitor these properties inherently carry safety risks for site technicians and operators. These risks are mostly related to working alongside construction traffic and also potentially in proximity to live traffic (depending on site specific traffic management). The use of automated technologies currently available to construction industry can reduce the above-mentioned risks.

The following objectives were identified:

O1. Review conventional test methods for all the areas considered

O2. Review innovative test methods for all the areas considered

O3. Selection of technologies which can be used in the UK

O4. Comparison and validation of the selected technologies with the conventional test methods, for the following areas: asphalt surface regularity, asphalt surface macro-texture and in-situ density

O5. Setting of acceptance criteria for QA

O6. Propose recommendations for future specifications

2. Methodology

The methodology stages adopted and key outputs are summarised in Table 1, and detailed below.

Table 1: Summary of Stages.

Stage	Output
Evaluation of conventional QC/QA test methods	State of industry review
Review of innovative test methods	Matrix assessment linked to Technology Readiness Level
Selection of options for potential adoption in UK	Interim report and presentation (including recommendations)
Validation trials	Robust designed trials with outputs for inclusion in the final report
Setting of acceptance criteria for QA	Validated approach for QA for inclusion in the final report
Summary of findings and recommendations for future work	Final report including the assessment of innovative test methods and recommendations for future specifications

2.1 Evaluation of conventional QC/QA test methods

Existing test requirements and methods were evaluated against the following criteria:

- Automation level
- Accuracy and precision (repeatability and reproducibility) linked to compliance requirements
- Test frequency (sample interval) and time (including measuring speed)
- Cost
- Benefits and Limitations

2.2 Review of innovative test methods

A literature review (including scientific publications, reports, standards and internet sources) was completed along with engagement with industry suppliers and manufacturers. The review identified technological advancement in construction plant and automation in quality monitoring equipment, as an alternative to the conventional QA practices.

The gathered information covered (but was not limited to) the following fields:

- Specification/Guidelines
- Data collection technique
- Automation level
- Accuracy and precision (repeatability and reproducibility) linked to compliance requirements
- Test frequency (sample interval) and time (including measuring speed)
- Cost
- Compatibility and correlation with other testing methods
- Calibration and certification process

- Contribution to Building Information Modelling (BIM)
- Potential use, e.g. use as research or QA/QC tools

The benefits and limitations of each technology are summarised in Section 3 and the Technology/Innovation Readiness Level (used by Highways England to assess innovative techniques and materials [1]) in Table 2 was used as guidance for benchmarking purposes.

Table 2: Assessment Procedure for 'Innovative' Techniques and Materials (adapted from Highways England) [1].

Readiness Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Technology validation in a laboratory environment
5	Technology basic validation in a relevant environment
6	Technology model or prototype demonstration in a relevant environment
7	Technology prototype demonstration in an operational environment
8	Actual technology completed and qualified through test and demonstration
9	Actual technology qualified through successful mission operations

2.3 Selection of technologies for potential adoption in UK

Following the review of the existing and new technologies available for quality and compliance testing, the technologies were selected based on a matrix assessment (Section 3). The relevant suppliers were engaged and site trials planned to compare and validate the selected technologies against the conventional methods (Sections 4, 5, and 6).

2.4 Validation trials

Field trials were undertaken to review and assess data collected by the selected technologies to:

- Understand the operation of the automated data collection systems and collect site data from both the innovative technologies and the conventional test methods
- Interrogate the data to find their correlation against the reference values by the conventional test methods
- Assess the accuracy and precision levels of the selected technologies and determine whether they are suitable as QC/QA measures

2.5 Setting of acceptance criteria for QA

To establish acceptance criteria for the selected technologies the following have been considered:

- Comparison method of the selected and conventional test methods

- Correlations between the selected and conventional test methods
- Influence of the selected technologies on compliance to current standards
- Repeatability and reproducibility of the selected test methods

2.6 Summary of findings and recommendations for future work

Where appropriate and supported by the validation trial, findings from the research stages were used to propose:

- Further research requirement
- Potential updates to the relevant specification and/or standard

3. Review of existing and innovative technologies

The following section details the information collected for the conventional and innovative technologies for quality control and quality assurance of asphalt pavement.

3.1 Surface regularity

Pavement roughness is one of the most important characteristics of pavement surfacing, as an indicator of functional performance and structural condition [2].

According to the ASTM definition, roughness is the deviation of a surface from a true planar surface with characteristic dimensions such as longitudinal profile, transverse profile, and cross slope that affect vehicle dynamics, ride quality, dynamic loads, and drainage [3–6].

BS EN 13036-6 defines unevenness as the “deviation of a pavement surface from a filtered true planar surface in wavelength range of 0.5 m to 50 m” [7]. According to this standard, any device able to obtain a real profile is valid for profiling as long as it satisfies the objective of the measurements. A profilometer system can be mechanical, acoustic, electro-optical or a video camera [8].

MCHW Table 7/2 [9] specifies the maximum permitted number of surface irregularities in sections of 75 m or 300 m long for the specified road categories.

Conventional methods used in the UK are rolling straight-edges testing for longitudinal regularity and 3 m straight-edge testing for transverse regularity in accordance with BS EN 13036-7 [10].

MERLIN (Machine for Evaluating Roughness using Low cost Instrumentation) provides discrete readings and reports the roughness in MERLIN scale which can be converted to International Roughness Index (IRI) through empirical calibration equations. This equipment was purposely designed for use in developing countries for its benefits including easy to use, low cost, low maintenance and reasonable accuracy.

Higher levels of precision (Class 1 ASTM E950) is offered by stationary (e.g. ROMDAS z-250 or Dipstick™) or walking profilometers (e.g. ARRB G3). However, as with the MERLIN, the main limitation of these systems is that an operator is needed to ‘walk’ them along the road.

Accelerometers can measure the relative movement in 3D, being able to detect pavement irregularities at higher speed. In this regard, two smartphone applications (RoadBump Pro and Roadroid Pro V2) were developed to make use of modern smartphone capabilities and real-time processes. Nevertheless, these systems are considered to have a relatively poor level of accuracy [11].

More accurate systems making use of accelerometers are used by Dynatest, ARRB, ROMDAS and ARAN, among others, typically for calculating the IRI. However, these commercial systems are generally employed as a support for validation and verification of other data collection systems (e.g. laser profilers).

In order to obtain a profile with a high level of accuracy (Class 1 ASTM E950), laser profilers are the most common techniques. In this regard, P3-AT and ALPS2 (Automated Laser Profile System 2) are two relevant research projects making use of laser technology to automatically measure regularity of pavement. Their measurement of IRI is comparable to that of the commercial ARRB Walking Profiler, their main advantages being the use for a joystick (for P3-PT) and the full carriageway cover (for the ALPS2), respectively.

Laser systems are amongst others used by Dynatest, ARAN, ROMDAS, Pathway Services Inc., International Cybernetics, LIMAB RoadRun, PaveTesting, AID, ERI, Pavision, PaveVision3D Ultra, HSP and SSI [11]. MATtest Laser Straight Edge (LSE) system uses a software which calculates a running 3 m straight line. Therefore, results can be correlated to the Rolling Straight Edge (RSE), which is the conventional method used for QA in UK. In this regard, this system can be of particular interest for the UK network.

A summary of reviewed technologies to measure surface regularity and their main characteristics is presented in Table 3. Products with limited information have been discarded, and similar techniques are grouped.

Table 3: Surface regularity detection methods

Methods	Straightedge and Rolling Straight Edge	MERLIN (Machine for Evaluating Roughness using Low cost Instrumentation)	Stationary Inclinometer DipStick™; ROMDAS z-250	ARRB Walking Profilometer G3	Smartphone apps (RoadBump Pro and Roadroid Pro V2)	Inertial Profilers - Dynatest 5051 Mk II and IV Road Surface Profiler; or in ARAN	Autonomous Robot (P3-AT)	Automated Laser Profile System (ALPS2)	MATtest Laser Straight Edge
Visual illustration									
Case study References	12,13,14,15,16,17,18, 19,20	21,22,23,24	2,17,21,22,23,25,26	21,22,23,25,27,28,29	30	2,31,32,33	34	12,17,23	35,36,37
Data collection technique	Manual reading	Manual reading	Inclinometer	Rolling inclinometer	Accelerometer	Accelerometer plus laser	Laser	Laser	Laser
Specification/ Guidelines	BS EN 13036-7 [38]; ASTM E1703-10; SHW Clause 702 [9]	ASTM E950 and E1364 [3]	ASTM E1364 [3][39]; User's guide	ASTM E950 and E1364; AG:PT/T450; [3,39,40]	AG:AM/T004; AG:AM/T002 [3]	ASTM E950 [3]; AASHTO R57; Owner's Manual	ASTM E950 [3]; AASHTO R57	[39]	BS EN 13036-7 [38]; SHW Clause 702 [9]
Automation	✗	✗	✗	✓ ✗	✓	✓	✓	✓	✓
Precision and accuracy	Accuracy ± 0.25 mm (Rolling Straight Edge)	Class 2*or 3*	Precision of ± 0.127 mm (DipStick); R^2 = 0.95 (with IRI measurement); Resolution ± 0.05 mm (ROMDAS)	Precision of ± 0.01 mm; Longitudinal precision of ± 0.045%	Class 3* or 4*	Accelerometer resolution: 9.81 x 10^{-6} m/s^2; Accuracy: ± 5% of the measurements by manual profiling	Resolution of ± 0.0005 mm	Class 1*	Class 1*; r = 11% (for 4 mm irregularities – see Section 4.4)
ASTM E950 Class	4	2	1	1	3-4	1	1	1	1
Travelling Speed	1-2 km/h	Walking speed	Approx. 3.2 km/h	4.8 km/h	Best results at 80 – 95 km/h. Data collection at 50 – 95 km/h	Up to 70 km/h	Up to 3 km/h	8-20 km/h	Up to 80 km/h

Methods	Straightedge and Rolling Straight Edge	MERLIN (Machine for Evaluating Roughness using Low cost Instrumentation)	Stationary Inclinometer DipStick™; ROMDAS z-250	ARRB Walking Profilometer G3	Smartphone apps (RoadBump Pro and Roadroid Pro V2)	Inertial Profilers - Dynatest 5051 Mk II and IV Road Surface Profiler; or in ARAN	Autonomous Robot (P3-AT)	Automated Laser Profile System (ALPS2)	MATtest Laser Straight Edge
Sample Interval		Variable	Every 250 mm (ROMDAS)	Every 241.3 mm	20 m - Roadroid	Every 25 mm	Every 150 mm	Every 6 mm	Every 1 m
Cost	£110-2000	£183	£3,300-8,037	£22,000	£77	£70,000-165,000		£7,334 excluding the software and the lawn tractor	N/A
Compatibility/ Correlation	Not correlated with other methods; IRI estimates	IRI and BI (fifth wheel bump integrator)	IRI	IRI	Poor correlation with IRI calculated from Class 1 devices	IRI; RN (Ride Number); Boeing Bump Index	IRI and RN	IRI	TRL device (RSE) by constantly calculating a running 3 m straight line; IRI
Calibration & Certification	BS EN 13036-7; SHW Clause 702	Calibration equations for different surfaces	User's guide (DCL, 2004)	AG:PT/T450	Vehicle/device calibration factor	ASTM E950; AASHTO R57			BS EN 13036-7; SHW Clause 702; in-house procedure H109
Contribution to BIM			Text File and RoadRuf/ ProVal file; Bluetooth compatible	PPF, ERD, RAW (proprietary binary), CSV		Roughness data can be exported to a variety of formats (ASCII, XLS, ERD, PRO)		CSV files (3D data set)	CSV files
Benefits	Relatively low cost; Portable	Robust; Easily calibrated; Easily built, used and maintained; Low cost	Compact and portable	Faster than Straightedge and DipStick; Bluetooth connectivity between unit and tablet; WiFi connectivity for data transfer	Great flexibility in roughness data collection; Low cost; Quicker/easier in-house data processing	Operate at traffic speed; "Stop & Go" functionality; Real time data collection, analysis & storage; Multifunctional: texture, rutting (only in III), pot holes	Can move using a joystick control or randomly; Lab. results comparable to commercial ARRB Walking Profilometer	Can cover full carriageway width	Operate at traffic speed (Up to 80 km/h)
Limitations	Time-consuming; Sparseness of measurements; Fixed measure base; Results operator-dependent	Sparseness of measurements; Need surface contact; Results operator-dependent; Relatively slow; Poor portability	Sparseness of measurements; Need surface contact; Relatively slow; Results operator-dependent	Sparseness of measurements; Need surface contact; Results operator-dependent; Relatively slow	Further processing after run; Not as accurate as other equipment; Affected by driving, wind and phone steadiness	Relatively high cost; Typically used as a complementary tool for validation and verification of laser profilers	Sparseness of measurements; Current version is missing an accelerometer; Relatively slow	Complex data processing; Not portable; Road closure required	Not portable
Research or QC/QA Tools	QC/QA	QC	QC/QA	QC/QA	Research / QC	QC/QA	Research / QC	Research / QC	Working towards QC/QA

Methods	Straightedge and Rolling Straight Edge	MERLIN (Machine for Evaluating Roughness using Low cost Instrumentation)	Stationary Inclinometer DipStick™; ROMDAS z-250	ARRB Walking Profilometer G3	Smartphone apps (RoadBump Pro and Roadroid Pro V2)	Inertial Profilers - Dynatest 5051 Mk II and IV Road Surface Profiler; or in ARAN	Autonomous Robot (P3-AT)	Automated Laser Profile System (ALPS2)	MATtest Laser Straight Edge
Technology Readiness Level	9	9	9	9	6	9	4	5	Working towards 9

*ASTM E950: Class 1 less than or equal to 0.1 mm; Class 2 greater than 0.1 mm to 0.2 mm; Class 3 greater than 0.2 mm to 0.5 mm; Class 4 greater than 0.5 mm

3.2 Surface macro-texture

Macro-texture is an important factor that contributes to the pavement skid resistance. It also provides drainage channels for water expulsion between the tyre and the pavement [41].

The performance indicators for macro-texture are the Mean Profile Depth (MPD) and the Mean Texture Depth (MTD). BS EN 13473-1 [8] defines MPD as the difference between the arithmetic mean of two peaks and the mean level on a 100 mm baseline. The MTD is estimated as the ratio between the volume of a gap-filling material (sand or solid glass spheres) and its footprint area [42]. MTD can be estimated from MPD by means of a transformation equation [8].

The conventional testing method for measuring texture depth is the volumetric patch technique, as described in BS EN 13036-1 [42].

MCHW clause 921 [43] specifies the spacing, the location and the upper and lower limit of the average texture depths for materials other than thin surface course systems, which are specified in clause 942 instead.

Close Range Photogrammetry is an innovative 3D modelling method developed by Ulster University to investigate surface texture. The data collection is based on camera images. Different volumetric properties can be extracted once the 3D dense point cloud is generated. However, this procedure needs image post processing with specific software/skills requirements, bringing down the level of automation.

The RoboTex and the Circular Texture Meter (CTM) are examples of equipment that use computer vision techniques. These research technologies make use of laser line scanning which can provide a 3D texture map. In this way macro-texture measurements can be directly compared with measurements obtained using volumetric methods. The CTM is a stationary apparatus while RoboTex is a robotic apparatus, both of them being not completely autonomous in detecting surface texture. These technologies allow for a rapid, dense and precise data acquisition.

The WDM Texture Meter (TM2) and the Transit NZ Stationary Laser Profiler (SLP) are examples of measuring instruments using single point laser for a high-precision measurement of the road surface. These commercially available technologies present a good correlation with Sand Patch. However, they still need the operator on site.

The above-mentioned technologies have in common relatively slow speed and low automation. These issues are overcome by vehicle-mounted systems which typically measure surface texture at traffic speed without the need for traffic disruption.

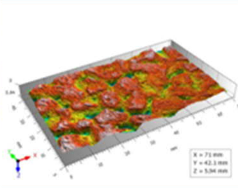
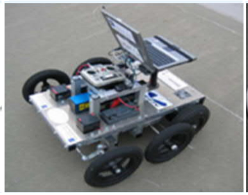
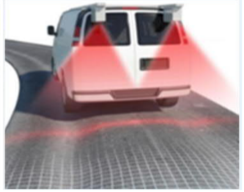
These technologies use a laser line scanning and camera for creating 3D surface reconstructions. This system is amongst others used by ARAN, ARRB Hawkeye, Dynatest, ROMDAS, ERI, Pavision, PaveVision3D Ultra, and SSI. A UK application of this system is the MATtest 3D-TD.

A common disadvantage is the high cost of the equipment, but the results generally correlate very well with field direct measurements.

An additional advantage of using laser-based technologies is that apart from macro-texture, cracks (and other pavement distress) can be detected and categorised, when a sufficiently high projection frequency is used. This principle is used in the Laser Crack Measurement System (LCMS).

The review of conventional and innovative technologies and their main characteristics to measure surface texture are summarised in Table 4. Products with limited information have been discarded, and similar techniques are grouped.

Table 4: Surface macro-texture measurement systems

Method	Volumetric patch technique	Close Range Photogrammetry 3D model (UUTex3D);	Computer vision techniques: RoboTex; Circular texture meter (CTM) (stationary)	WDM Ltd Laser Texture Meter TM2	Transit NZ Stationary Laser Profiler (SLP)	LCMS (Laser Crack Measurement System) - 3D road scanning and texture	Dynatest 5051 Mk IV	MATtest 3D-TD Laser scanning
Visual illustration								
Case study References	41,44,45,46	47	13,41,48,49,50,51	52,53,54	27,28,44,55,56,57	44,56	31,32,33	35,37,58
Data collection technique	Manual	Camera (wide range of cameras can be used)	RoboTex: 1 kHz Laser line approx. 100 mm wide	Single 16 kHz Laser line	Single 32 kHz Laser along the 1.7m beam	3D Profiler: Laser line plus camera	3D Profiler: Laser line plus camera	3D Profiler: Laser line plus camera
Specification/ Guidelines	BS EN 13036-1 [59]		BS ISO 13473-3 [60]	BS ISO 13473-3 [60]	AUSTROADS BS.A.65 [39]	BS ISO 13473-3 [60]	ASTM E1845-01; ISO 13473-1	BS ISO 13473-3 [60]
Automation	✗	✓ ✗	✓ ✗	✓ ✗	✓ ✗	✓	✓	✓
Precision and accuracy	BS EN 13036-1: r = 0.166 mm R = 0.321 mm (Validity range: 0.5 mm – 1.2 mm)		RoboTex: Lateral resolution of 0.5-1.0 mm; Vertical resolution of ±0.01 mm; CTM: r = 3.2% R = 5.9%	Vertical resolution of <±0.05 mm; Longitudinal resolution of ±0.5 mm; Transversal resolution of ±1.0 mm;	Vertical resolution of ±0.0008 mm; Horizontal resolution of ±0.3 mm; r < 1%	Vertical resolution of 0.1-0.25 mm; Longitudinal resolution ±1 mm; Lateral resolution ±1 mm; r < 0.5%	Complies with ASTM E1845-01 and ISO 13473-1 Macro-texture; Longitudinal resolution ±1 mm;	r = 4% (see Section 5.4)
Travelling Speed			RoboTex:1.8 km/h CTM: N/A	3-5 km/h (walking speed)	N/A	100 km/h	Traffic speed (70 km/h)	Up to 80 km/h
Sample Interval	Every 5 m		RoboTex: (width: 100 mm) CTM: 0.9 mm	Every 2-5 mm (width: 100 mm)	Every 0.3 mm (width: 1.67 m)	5.600/28.000 profiles; Adjustable profile spacing		Every 1 m
Cost	Relatively low cost						£73,373-165,000	N/A

Method	Volumetric patch technique	Close Range Photogrammetry 3D model (UUTex3D);	Computer vision techniques: RoboTex; Circular texture meter (CTM) (stationary)	WDM Ltd Laser Texture Meter TM2	Transit NZ Stationary Laser Profiler (SLP)	LCMS (Laser Crack Measurement System) - 3D road scanning and texture	Dynatest 5051 Mk IV	MATtest 3D-TD Laser scanning
Compatibility/ Correlation between different systems	MTD and MPD	Volumetrics	CTM: Correlation with Sand Patch: MTD= 1.03*MPD+0.15	MPD and RMSTD.	MPD Correlation with Sand Patch and LCMS (R^2 > 0.9)	MTD Correlation with SLP (R^2 > 0.9)	Correlation of macro-texture to friction and skid resistance	MTD Correlation with Sand Patch (R^2 > 0.94) (see Section 5.2)
Contribution to BIM		Polygon file format (ply) Mesh (.xyz) Text (.txt)		Different types of formats		Different types of formats (CSV, Shp, KML, Access)	Data can be used for project and network evaluation and in Pavement Management Systems (.rsp file)	Different types of output format (Shp, CSV, etc.)
Benefits	Low cost; Compact	Operate at traffic speed; Data redundancy; Extensive photographic documentation	Compact	Compact; Capable of operating continuously for approximately 10 hours	High resolution	Continuous; Can measure 4 m lane width; Operate at traffic speed (up to 100 km/h); No traffic disruption; Multifunctional: cracking, ravelling (R^2 = 0.93 with Visuals), rutting, pot holes	Continuous; "Stop & Go" functionality; Operate at traffic speed; No traffic disruption; Real time data collection, analysis & storage; Multi-functional: cracking, rutting, regularity	Continuous; Operate at traffic speed; No traffic disruption; Real time data collection, analysis & storage
Limitations	Operator-dependent; Sparseness of measurements; Relatively slow	Research stage; Software/Skills required for data processing	Sparseness of measurements; Poor correlation with Sand Patch for open-graded mixtures	Sparseness of measurements; Relatively slow (up to 5 km/h)	Sparseness of measurements	Relatively high cost	Relatively high cost	Loss of accuracy for 14 mm aggregate (See Section 5.2)
Research or QC/QA Tools	QC/QA	Research	Research	QC/QA	QC/QA	QC/QA	QC/QA	Working towards QC/QA
HE Technology Readiness Level	9	4	5	7	9	9	9	Working towards 9

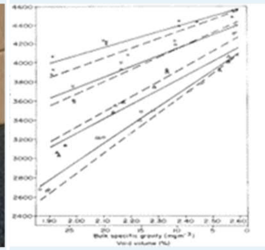
3.3 In-situ density

Compaction is an essential process in asphalt pavement construction to ensure long-term durability. Density, air voids and binder content have significant roles on the in-situ performance of road pavements. Air voids content being either too high or too low can lead to premature failure: high voids content as a result of poor compaction can result in water penetration and defects such as cracking and ravelling; on the other hand, very low voids content may also lead to rutting and permanent deformation [61].

The voids content is determined in accordance with BS EN 12697-8 [62] after measuring the bulk density and the maximum density of specimens. The bulk density and maximum density are determined in according to BS EN 12697 Parts 6 [63] and 5 [64], respectively. Two commonly used methods of measuring in-situ density of asphalt layers are core density and nuclear density gauge. The former requires extraction of core samples from site for laboratory assessments. This is the only direct measurement of the asphalt density. However, the process of core extraction, measurements, testing and logging is time-consuming and costly. The nuclear gauge is a faster and non-destructive alternative solution, but has practical limitations and health and safety risks due to its use of radioactive material [61].

Alternative methods have been investigated for safer, more cost-effective and easier-to-operate solutions. Electromagnetic devices for density measurements were made commercially available in the late 1990s. Other technologies that claimed to be successful alternatives for measuring in-situ asphalt densities are also summarised in Table 5. Some are still at the research stage and not commercially available.

Table 5: Asphalt in-situ density measurement systems

Methods	Core density	Nuclear Density Gauge Troxler Model 4640-B	Electrical impedance principles - Pavement Quality Indicator (PQI) 380	PaveTracker™ Troxler Model 2701b	Ultrasound and Ultrasonic waves	Ground Penetration Radar (GPR) and Step Frequency Radar (SFR)	GPR PaveScan® RDM GSSI
Visual illustration							
Case study References		65,66,67,68,69,70,71,72,73,74,75, 76,77,78,79,80	66,67,73,78,80	65,66,67,68,69,73,81	82,83	66,70,71,72,84,85,86,87,88, 89	90,91
Specification/ Guidelines	BS 594987 [92]; BS EN 12697-6 [93]	BS 594987 [92]; ASTM D2950-14 [94]	BS 594987 [92]; ASTM D7113 [95]; AASHTO T343-12 [96]	BS 594987 [92]; ASTM D7113 [95]; AASHTO T343-12 [96]			
Automation	✗	✗	✗	✗		✓	✓ ✗
Precision and accuracy		Accuracy of ±0.3%	Comparable with other Non-nuclear devices	Accuracy of ±2.4%		GPR 'comparable to, or better than, that of nuclear gauge'; SFR 'accuracy close to the compaction provided by standard tests'	Accuracy of ±0.12 (dielectric)
Repeatability and Reproducibility Standard Deviation	(BS EN 12697-6) r = 8-28 kg/m^3 R = 22-82 kg/m^3	(ASTM D2950) r < 25.15 kg/m^3 R < 70.48 kg/m^3	(ASTM D7113) r < 20.50 kg/m^3 R < 23.55 kg/m^3	(ASTM D7113) r < 20.50 kg/m^3 R < 23.55 kg/m^3		SD about half that of nuclear gauge	r = ±0.12 (dielectric)
Instant measurement	No	1-4 minutes	5 seconds	2 seconds	Instant	Instant	Instant (measurement speed: 4.8 km/h)
Compatibility/ Correlation between different systems	N/A	Correlation with core bulk density measurement	Correlation with core bulk density measurement	Correlation with core bulk density measurement	R^2 range: 0.92-0.94 between ultrasonic measurement and core bulk density measurement	Correlation with core bulk density measurement. R^2 very variable but up to: 0.92	Correlation with core bulk density measurement. R^2 very variable

Methods	Core density	Nuclear Density Gauge Troxler Model 4640-B	Electrical impedance principles - Pavement Quality Indicator (PQI) 380	PaveTracker™ Troxler Model 2701b	Ultrasound and Ultrasonic waves	Ground Penetration Radar (GPR) and Step Frequency Radar (SFR)	GPR PaveScan® RDM GSSI
Calibration and Certification process		General calibration according to ASTM D7759 and D7013; Calibration Range: 1762-2723 kg/m^3	Annual Core calibration according to ASTM D7113	Core calibration according to ASTM D7113	Core calibration	Core calibration	Core calibration
Benefits	High repeatability	NDT (Non-Destructive Test); Minor impact by temperature	NDT; Faster than nuclear; Lightweight and easy to use; Minor impact by temperature but needs calibration	NDT; Lightweight and easy to use; Minor impact by temperature but needs calibration	NDT; Instant readings	NDT; Instant readings; Continuous measurement along the lane	NDT; Instant readings; Faster measurement speed than other NDT methods; From 1 to 3 sensors operating at the same time for a wider coverage; Continuous measurement along the lane; GPS location
Limitations	Destructive Test; Time-consuming; Not-automatic	Licensing; Radiation shield; Time-consuming; Training; Storage issues; Heavy; High maintenance cost; Less precise than cores; Not-adjustable for area	Cannot use near electromagnetic force fields, e.g. high voltage power line or large metal objects; Dielectric devices are usually sensitive to moisture, although spec states "not affected by moisture"	Cannot use near electromagnetic force fields, e.g. high voltage power line or large metal objects; Dielectric devices are usually sensitive to moisture, although spec states "no moisture correction needed"	Limited information on density measurement	Testing in dry condition only	Cannot use near electromagnetic force fields, e.g. high voltage power line or large metal objects; Dielectric devices are usually sensitive to moisture
Research or QC/QA Tools	QC/QA	QC/QA	QC/QA	QC/QA	Research	QC	Working towards QA/QC
Technology Readiness Level	9	9	9	9	3	7	Working towards 8

3.4 Intelligent compaction

Originally developed in 1980s for soil and sub-base and then adapted for asphalt pavement in 1990s, the concept of Intelligent Compaction (IC) was to use rollers that can modify the compactive effort to produce asphalt pavements with the desired stiffness [97]. In theory the stiffness could be correlated to the in-situ density, providing a real-time tool for assessing compliance requirements [97]. However, the uptake of IC for real-time density measurement has been limited due to it being relatively unproven for asphalt [61]. This is because measured stiffness can be affected by temperatures, loading rates, material thickness and the stiffness of the underlying layers. Hence, any change in the measured stiffness may or may not be caused by the variation in the material density [71].

The correlation between stiffness (or similar parameters measured by IC systems) and density is still being investigated [97], however, these methods gained favour especially in the US under the regulation by AASHTO [98]. A recent investigation on suitability of IC methods for asphalt pavement QC and QA concluded that IC can improve both the compaction coverage and the compaction for QC applications. However, no solid evidence is available to support the possibility of substituting core density values with IC for QA [99].

Equipment developed and used worldwide typically includes a compaction measurement value, GPS-based documentation, on-board color-coded display, surface temperature measurement and automatic feedback system [97]. This enables the roller operator to track the roller passes and make adjustment to the compaction patterns [61]. A generic illustration of how an intelligent compaction system may be setup is presented in Figure 1.

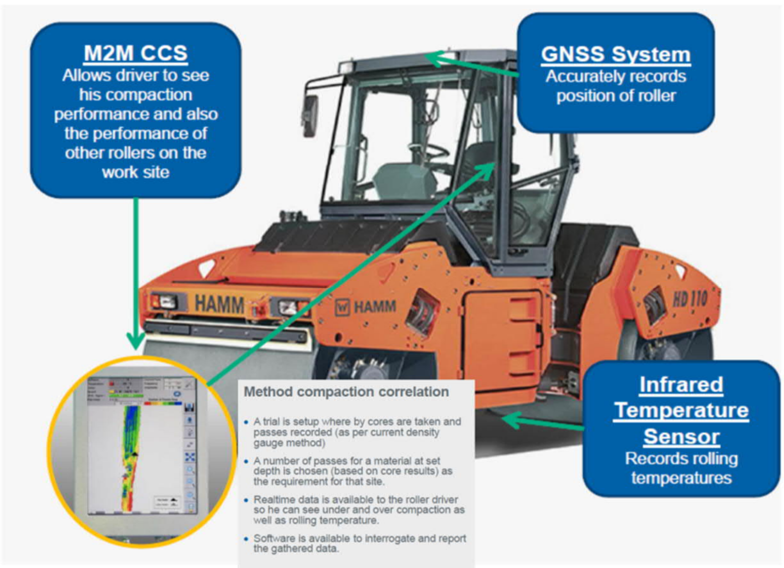
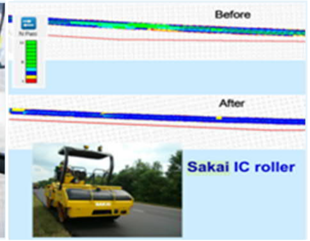


Figure 1 – Intelligent Compaction System (image courtesy Aggregate Industries)

The IC technologies reviewed and their main features are reported in Table 6.

Table 6: Intelligent compaction – automatic feedback system capable of varying compactive effort based on measured stiffness

Manufacturer	BOMAG Asphalt IC System	Volvo Density Direct	Caterpillar	Dynapac US	Sakai Asphalt IC System
Visual illustration					
Case study References	100,101	102,103,104	100,105,106	100,107	100,105,108,109
Specification/ Guidelines	AASHTO PP81-14; FHWA-Asphalt-IC-Spec-2014 [98][110]	AASHTO PP81-14; FHWA-Asphalt-IC-Spec-2014 [98][110]	AASHTO PP81-14; FHWA-Asphalt-IC-Spec-2014 [98][110]	AASHTO PP81-14; FHWA-Asphalt-IC-Spec-2014 [98][110]	AASHTO PP81-14; FHWA-Asphalt-IC-Spec-2014 [98][110]
Measuring system	Vibration Modulus (E_{vib})	Compaction Meter Value (CMV)	Compaction Meter Value (CMV)	Compaction Meter Value (CMV)	Compaction Control Value (CCV)
Other characteristics	Auto Feedback Control; GPS-based colour-coded mapping of materials stiffness, mat temperature and roller passes	Auto Feedback Control; GPS Geolocation: differential GPS (accuracy of ±12.7 mm); Pass mapping, temperature mapping and real-time density calculation; Density calculation over the full mat surface	Auto Feedback Control; Positioning GNSS; Colour-coded mapping of mat temperature and roller passes; A "composite stiffness value" indicates stiffness of the current and supporting layers beneath the drum	Auto Feedback Control; Positioning GNSS; Colour-code mapping of temperature and roller passes	Auto Feedback Control; Positioning GPS; Colour-coded mapping with pass count & coverage, stiffness, temperature of the mat
Compatibility/ Correlation between different systems		Bulk Density	Bulk Density (poor correlation reported [105])	Bulk Density	Bulk Density
Research or QA/QC Tools	QC	QC	QC	QC	QC
Technology Readiness Level	9	9	9	9	9

3.5 Pavement distresses

The measurement of pavement distress is fundamental to assessing pavement condition and planning or executing minor maintenance interventions or rehabilitations. Pavement condition can be evaluated either manually or automatically.

Traditionally, serviceability surveys are conducted periodically through visual inspection of pavements to identify and classify any existing distress.

Manual pavement inspection depends on the specialist's knowledge and experience of the practitioner. Therefore, it is prone to subjective scoring [11,111] and results are often affected by problems associated with variability and repeatability. In addition, this type of survey is labour-intensive and slow and the inspections are costly and risky for the personnel [11,112].

Increasing the automation level of distress detection systems represents a challenge for road authorities. Extensive research has been conducted on pavement distress detection [11]. Latest developments in computer science offer several possibilities for automated detection and classification of pavement distress [11]. Semi-automatic systems enable the distress identification in the post-processing by video-recording the road condition. It helps to improve safety but still relies on operator's experience on distress identification. Therefore, automated distress detection methods have been developed to reduce subjective scoring of inputs, which are then used in quantitative analysis.

There are various pieces of equipment used to identify distress and road condition, such as cameras, laser, accelerometers, radar, and acoustic systems, among others. An extensive review of these systems is provided by Coenen and Golroo [11].

Almost all inspection vehicles are equipped with a camera. Single cameras and video cameras (area-scan cameras) provide a 2D result. For these systems, high levels of illumination are needed to visualise the cracks and exclude unwanted shadows and other light noise. An example of vehicle with video camera with high level of illumination is given by the WDM RAV.

Line-scan cameras overcome the requirement for illumination. In this regard, the AMAC vehicle, the Laser Road Imaging System (LRIS), the TRL Harris2 system, the CSIRO (Australian Commonwealth Scientific and Industrial Research Organization), and the RoadCrack vehicle are examples using line-scan cameras in combination with laser illumination for a clear crack visibility [11].

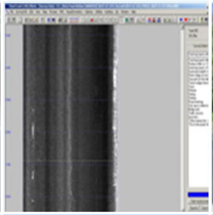
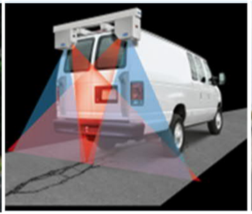
3D pavement visualisation can be created by using stereo imaging with two (and preferably more) cameras. However, this method has relatively low accuracy and requires relatively high calculation power so that only a few research studies have been conducted [11].

One of the most used techniques for creating 3D pavement reconstruction is laser scanning, using a laser line and a camera at an angle that detects the shape of the line, based on which the depth of the surface is evaluated. This is the principle used in the commercial Laser Crack Measuring System (LCMS) [11]. Another example is given by the Automated Road Condition Survey (ARCS) system developed by Georgia Tech.

The infrared spectroscopy represents a potential alternative in predicting fretting. By measuring the changes in the chemistry of the asphalt may help early detection of fretting, as shown by laboratory testing of aged binder. The possibility of increasing the automation and speed of this non-destructive technology is being investigated by Bowden et al. [113,114].

A review of conventional and innovative technologies and their main characteristics has been undertaken and summarised in Table 7. Products with limited information have been discarded, and similar techniques are grouped.

Table 7: Pavement distresses detection systems

Methods	Operator Visual Inspections	WDM Ltd RAV; (also Jacobs-Babtie TTS)	TRL/HA - Highways Agency Road Research Information System (HARRIS2)	CSIRO (Australian Commonwealth Scientific and Industrial Research Organization), RoadCrack™ vehicle	Canada's National Optics Institute (INO) Laser Road Imaging System (LRIS) high-resolution 2D imaging system; WayLink Automated Distress Analysis (ADA)	AMAC® (Multifunctional device for road analysis)	ARAN (Automatic Road Analyzer) 9000 with LCMS	Automated Road Condition Survey (ARCS) System by Georgia Tech	Infrared Fourier Transform Infrared Spectroscopy (FTIR) Spectroscopy
Visual illustration								 	
Case study References	56,111,112,115,116, 117,118	119,120	112,116,117,119	112,119,121	11,112,119,122	11,123,124	56,125,126	118	113,114,127,128
Automation	✗	✓	✓ ✗	✓	✓	✓	✓	✓	✓
Data collection technique	Visual	Four standard video cameras with synchronised flash lighting	Three line-scan cameras; halogen lighting	Four line-scan cameras and continuous lighting	Line-scan; Laser illumination	Line-scan; Laser illumination	3D Profiler: Laser line plus camera	3D Profiler: Laser line plus camera	Infrared Spectroscopy
Precision and accuracy		Pixel resolution: approx. 2 mm	Pixel resolution 2 mm Local alignment: 1 – 2 m Pavement Profiling System (PPS) Sample Interval: 25mm transversely	1 mm resolution	1 mm resolution	2 mm wide and 1 m length cracks	1 mm transverse resolution; 1 – 5 mm longitudinal resolution; 0.05-0.5 mm vertical resolution; distance accuracy ± 0.02%	Transverse resolution:1 mm; Longitudinal resolution: 5 mm; Depth precision: 0.5 mm	Data collected at a spectral resolution of 4-8 cm^{-1}
Distress type	All distresses	Cracks, rutting, edge defects	Cracks	Cracks	Cracks	Cracks, rutting	Cracks (Alligator, Longitudinal, Transverse),	Cracks, rutting and ravelling	Binder aging, fretting

Methods	Operator Visual Inspections	WDM Ltd RAV; (also Jacobs-Babtie TTS)	TRL/HA - Highways Agency Road Research Information System (HARRIS2)	CSIRO (Australian Commonwealth Scientific and Industrial Research Organization), RoadCrack™ vehicle	Canada's National Optics Institute (INO) Laser Road Imaging System (LRIS) high-resolution 2D imaging system; WayLink Automated Distress Analysis (ADA)	AMAC® (Multifunctional device for road analysis)	ARAN (Automatic Road Analyzer) 9000 with LCMS	Automated Road Condition Survey (ARCS) System by Georgia Tech	Infrared Fourier Transform Infrared Spectroscopy (FTIR) Spectroscopy
							macro-texture, rutting		
Benefits	Most worldwide used method	Real-time processing; Operates at 100 km/h; Can cover 3.2 m lane width; Independently accredited by annually TRL	Continuous; Can cover 2.9 m lane width; Operate at up to 80 km/h	Continuous; Real time processing; Crack type classification; Operate at 5km/h to 100km/h	Dynatest automated crack characterization software (Waylink ADA) can rate the pavement crack condition while the van is collecting images data	Continuous; Laser: light condition has almost no effect on the quality of acquired images; Operate at traffic speed	Insensitive to the colour disturbance; 3D systems take advantage of depth info: Detect and quantify cracking, rutting, texture, potholes, shoving, ravelling and roughness; Operate at up to 80 km/h Can cover 4 m lane width	Insensitive to the colour disturbance; Unlike the laser profiler, collecting only two laser lines, the 3D line laser imaging system can capture 3D full-lane-width pavement surface data	
Limitations	Lack of consistency among operator criteria; High personal costs; Time-consuming	Measurement performance get worse when moving down the network hierarchy	Post-processing; Data from successive surveys is not perfectly aligned; Require manual interpretation of the images	Survey width = 2.25m	2D systems rely only on colour and intensity information, thus, are not able to discriminate dark areas not caused by pavement distress: tire marks, oil spills, etc.	Results on bridges are not as good as results on cracks and joints	The 3D laser scanners used in the presented system are much more expensive than traditional cameras at the same resolution	The 3D laser scanners used in the presented system are much more expensive than traditional cameras at the same resolution	Research stage; Successful application in static testing only
Technology Readiness Level	9	9	8	9	9	7	9	7	4

3.6 Asphalt temperature

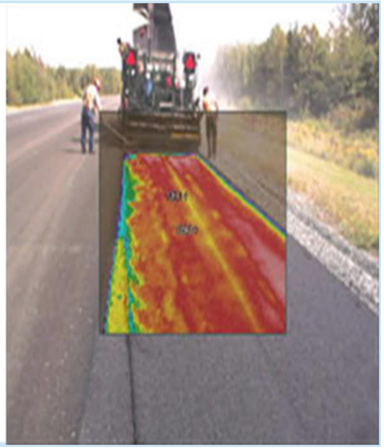
Temperature monitoring is essential in asphalt pavement construction because of the influence that temperatures (material, ground and air) have on the end product. This includes compaction and ride quality of the asphalt pavement.

The operation of dipping a temperature probe in the material is slow and inherently carries safety risks for operators when they work alongside construction traffic and also potentially in proximity to live traffic (depending on site specific traffic management).

Contact-free automatic tools have been developed and adopted for real-time screening, to improve construction quality and efficiency. The infrared wave detection tools provide instant temperature measurements based on material heat radiation without the need to be in contact with the material. These need to be calibrated to a reference method, for example a temperature probe. Considering the differences in the technologies, the surface temperatures measured by infrared are likely to differ from the under-surface temperature measured by probes. However, this discrepancy may not be as obvious in the hopper or the augers.

Main features of these two measurement systems are reported in Table 8.

Table 8: Asphalt temperature measurement systems

Methods	Contact Temperature Measuring Thermometer	Infrared Thermometer
Visual illustration		 
Photos References	[129]	[131][132]
Typical Product References	Controls Group Asphalt Digital Thermometer [130]	Land Instrument RT8A [133] Thermocouples [134]
Specification/ Guidelines	BS EN 12697-13 [135]	BS EN 12697-13 [135]
Automation	✗	✓
Precision and accuracy	Resolution 0.1 – 1.0 °C Accuracy of ±0.2% full scale	Resolution <0.1 °C Accuracy of <0.5% of measuring span
Repeatability and Reproducibility Standard Deviation		r = 0.01 R = N/A
Weight (kg)	0.235 kg	1.4 kg
Benefits	Relatively low cost	Measurements taken from a distance; Faster and safer than contact thermometer; Can gather more data with auto-save capability
Limitations	Slow process; Risk of exposure to concentration of asphalt fumes and high temperature	Can only measure surface temperatures
Research or QC/QA Tools	QC/QA	QC/QA
Technology Readiness Level HE (estimated)	9	9

3.7 Selection of innovative technologies

A wide range of innovative technologies and products have been included in the review. Their readiness ranges from early-stage research, such as UUTex3D, to fully-developed and commercially available devices, such as 3D-TD. The level of automation varies from semi-automatic equipment, such as ARRB Walking Profilometer, to fully-automated, vehicle-mounted equipment, such as laser straightedge.

An objective of this study is to compare and validate the innovative technologies with the conventional test methods. Thus, the technologies with high automation level, fast measurement speed, experience on the Strategic Road Network (SRN) and most importantly, good availability in the UK are considered more suitable for the purpose of this study.

Hence, the options selected for further assessment are:

- Laser Straight Edge (LSE) for surface regularity measurements
- 3D-TD for surface texture measurements
- PaveScan in-situ density system
- APEX, Roller and PAVE-IR automated systems as intelligent compaction technology and temperature measurement

The following sections describe the evaluation of each individual technology and summarise the findings at the end of each section.

4. Laser based system to measure surface regularity

This section details the assessment of Laser Straight Edge (LSE) as innovative technology to measure asphalt surface regularity against conventional Rolling Straight Edge (RSE).

4.1 Introduction

The Laser Straight Edge (LSE) is a vehicle mounted device designed to measure longitudinal surface irregularities in an automated and safe way. This method can be used at traffic speed up to 80 km/h without the need for expensive road closures [136].

The vehicle mounted laser system (Figure 2) comprises of a radar distance measuring device, laser height measuring system designed for use on a vehicle, an accelerometer used to exclude vehicle movement, GPS and software which mimics the Rolling Straight Edge (RSE) device moving over the profile [36,137].

Figure 2 – Vehicle mounted Laser Straight Edge system (courtesy of MATtest Ltd)

The LSE system used in this study includes a Class 1 (ASTM E950) [3] laser which operates at 2.5 kHz to measure the road profile. An internal algorithm simulates the traditional RSE by calculating the differences between the profiles and the measurements at the midpoints on a running 3 m straight line. The LSE output files provide the maximum deviations for every 1 m, whilst the RSE records the data where an excess of the threshold values is detected [137].

4.2 Data analysis

Comparative data sets (LSE and RSE) from the following sites were available for analysis:

- M1 Junction 5 (High Friction Surfacing)
- M25 Junction 25 (High Friction Surfacing)
- M25 Junction 28 (High Friction Surfacing)
- M25 Junction 23 (High Friction Surfacing)
- M4 Junction 4 (High Friction Surfacing)
- M4 Junction 4 Heathrow Spur Road (Clause 942 TSCS)
- A76 North of Garleffan (Surfacing complying with Transport Scotland TS 2010)
- A82 Garshake Road (Surfacing complying with Transport Scotland TS 2010)
- M8 Junction 27 Arkleston (Surfacing complying with Transport Scotland TS 2010)
- M1 Junction 16-19 (Clause 942 TSCS)
- A269 Ninfield Road (Clause 942 TSCS)
- A46 Hobby Horse to Widmerpool (Clause 942 TSCS)

A various range of surfacings was explored: most of the materials were compliant to Clause 942, other sites used high friction surfacings (with lower macro-texture) whereas few data are from the Scottish network. The LSE survey used GPS coordinates, whilst the RSE typically referred to local chainages. The information to accurately convert one to another was not available. Therefore, the point-to-point comparison was not practical. Considering that only the maximum number of surface irregularities in a given length (75 m or 300 m) are specified in MCHW1 Clause 702 [9], the data comparison was made on the basis of the total number of irregularities recorded for each section. The total number of irregularities above 4 mm, 7 mm and 10 mm obtained from LSE and RSE was compared for every 300 m section or less in each site. See Appendix A.

Visual verifications were used to match the start and end points of each section for conventional and laser surveys.

It is worth mentioning that RSE only records one irregularity if it stays above the threshold. The count increases to two only when it drops below the threshold and bounces back. Following the same principle, if a peak spreads over 2 consecutive metres, LSE only records one single irregularity [138].

The number of surface irregularities above the threshold values of 4 mm, 7 mm and 10 mm are presented in Figure 3, Figure 4 and Figure 5 for the available datasets, respectively. See Appendix A.

Overall, LSE results appear consistent with RSE outcomes. The two methods reported the same number of irregularities in approximately 80% of the sections analysed. Nevertheless, this value is affected by the relatively low number of irregularities above 7 mm and 10 mm. Considering the irregularities above 4 mm alone, the two methods provided the same result in 55% of the sections.

To quantify these discrepancies, the absolute difference in total number of irregularities detected by LSE and RSE has been evaluated for each section. The average figure of these differences considering all the sections analysed is:

- 0.82 number of irregularities for 4 mm irregularities
- 0.19 number of irregularities for 7 mm irregularities
- 0.07 number of irregularities for 10 mm irregularities

The influence of these differences on the compliance to standards is analysed in the following section.

4.3 Compliance results

Table 10 reports the LSE and RSE compliance results to MCHW 1 Clause 702 Table 7/2 [9] (see Table 9).

Table 9: MCHW 1 Clause 702 Table 7/2 Maximum Permitted Number of Surface irregularities [9]

	Surfaces of each lane of carriageway, each hard strip and each hard shoulder for each irregularity limit				Surfaces of each lane of bituminous binder courses for carriageway, hard strip and each hard shoulder for irregularity limit				Surfaces of lay-bys, service areas, and associated bituminous binder courses for each irregularity limit			
Irregularity Limits	4 mm		7 mm		4 mm		7 mm		4 mm		7 mm	
Length (m)	300	75	300	75	300	75	300	75	300	75	300	75
Category A* Roads	20	9	2	1	40	18	4	2	40	18	4	2
Category B* Roads	40	18	4	2	60	27	6	3	60	27	6	3

* The Category of each section of road is described in contract specified Appendix 7/1

Table 10: Compliance results

Site	Compliance to MCHW 1 Table 7/2 based on: LSE	RSE
M1 J5	Pass	Fail (7 mm)NOTE 1
M25 J25	Pass	Pass
M25 J28	Pass	Pass
M25 J23	Pass	Pass
M4 J4	Pass	Pass
M4 J4 Heathrow Spur Road	Pass	Pass
A76 North of Garleffan	PassNOTE 2	Fail (10 mm)NOTE 2
A82 Garshake Road	Pass	Pass
M8 Arkleston	Pass	Pass
M1 J16-J19	Pass	Pass
A269 Ninfield Road	Fail (7 mm and 10 mm)	Pass
A46 Hobby Horse to Widmerpool	Pass	Pass

NOTES:

1) The section was approximated to 75 m for the criterion for a compliance assessment.
2) The two 10 mm irregularities detected by RSE were on joints. These joints were not included within the LSE survey.

The two methods appear to give comparable compliance results with the exceptions of M1 J5, A76 North of Garleffanand and A269 Ninfield Road. The A269 runs through small towns/villages including several junctions and has numerous iron works. In this regard, as per MATtest reports and comments [138], the discrepancies could be due to the different paths along the LSE and RSE surveys. RSE surveys would typically avoid white lining, iron works and other road features; whilst LSE is more likely to drive over these features in a straight run.

Overall, there is a trend that LSE appears to have identified more surface irregularities than RSE. It is arguable that the travel paths explain the discrepancy in full. However, this may be an indication that LSE is a more rigorous measurement system compared to RSE.

4.4 Repeatability test

To evaluate the repeatability of LSE, a single 974 m length was tested ten times using the same LSE equipment by the same operator. The site location for this was Hitchin Road, Hertfordshire. The sample interval was every 1 m. Figure 3 plots the irregularity amplitude over the whole length for the ten runs.

According to ASTM E950 [3], at least ten repeated pavement profile measurements shall be used for a pavement section of 320 m with a sample interval of 0.3 m. In this regard, the repeatability test was carried out for a longer section but maintaining approximately the same total number of measurements i.e.: 974 measurements versus the ASTM requirement for 1057.

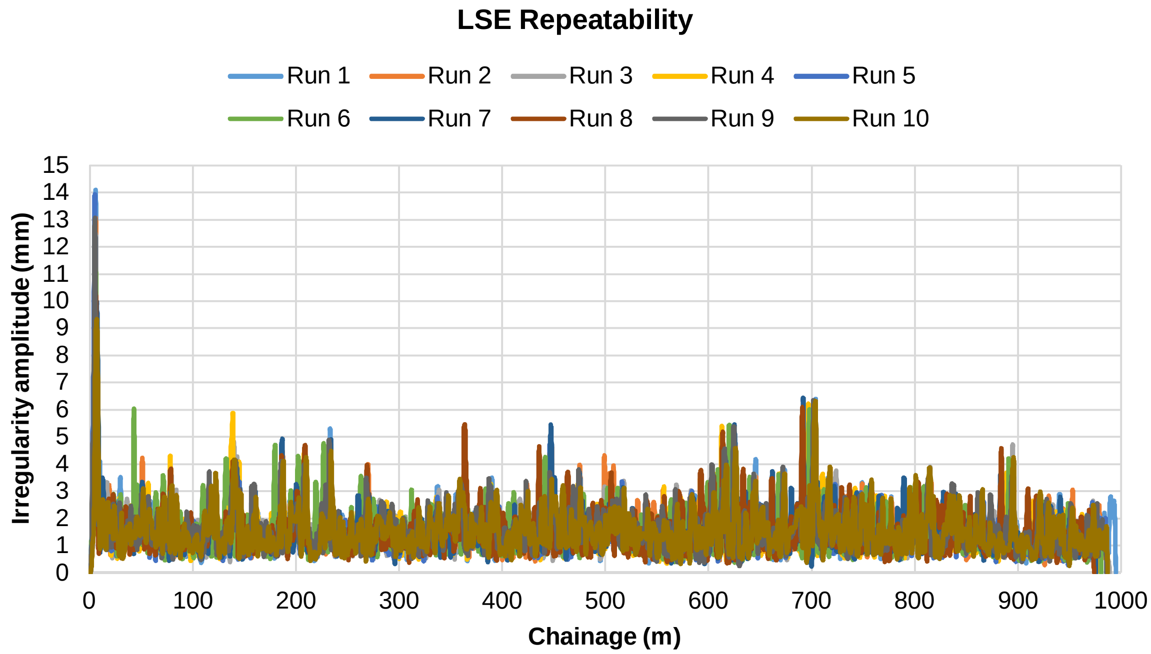


Figure 3 – MATtest LSE repeatability trial results

Table 11 reports the total number of irregularities in each run. The repeatability [139,140] of results was relatively high (repeatability error of 11%) for 4 mm irregularity. On the other hand, relatively low repeatability was observed for 7 mm and 10 mm irregularities (repeatability error of 51% and 63%, respectively). These last findings may be skewed by the relatively low number of irregularities in the first 10 m of survey, where a joint from one material to another was present [137]. To eliminate this factor, the repeatability error was also calculated excluding the first 10 m, as reported in the last column of Table 11.

Table 11: Total number of irregularities above 4 mm, 7 mm, and 10 mm recorded along the section for each run

No. of irregularities >	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean [a]	SD [b]	Relative Repeatability Error [c]=[b]/[a] (%)	Relative Repeatability Error Without first 10 m [c]=[b]/[a] (%)
4 mm	15	12	13	16	12	16	14	14	13	12	13.7	1.6	11%	13%
7 mm	0	2	2	1	2	2	3	2	1	3	1.8	0.9	51%	0%
10 mm	2	1	1	1	1	1	0	1	1	0	0.9	0.6	63%	0%

The rolling straight edge test was not carried out for the given section.

4.5 Summary of findings

The comparative method used for this analysis showed that the vehicle mounted Laser Straight Edge (LSE) matches, in the majority (80%) of locations, the total number of irregularities measured using the conventional Rolling Straight Edge (RSE).

LSE appears to detect a higher number of irregularities. This could be due to the different path along the LSE and RSE, which would normally avoid white lining and other road features.

These discrepancies did not seem to affect the final outcomes (compliance to specification). In this regard, more work would increase the confidence of these findings.

The repeatability trial indicates a relatively high consistency in capturing irregularities above 4 mm whereas repeatability deteriorated for measurement of 7 mm and 10 mm irregularities. The small number of 7 mm and 10 mm irregularities skewed the results (see Table 11). However, excluding the first 10 m, the detection of irregularities above 7 mm and 10 mm provided very consistent results. Nonetheless, it is important for a reproducibility study to be conducted in the future to verify the current results.

Overall, based on the data sets analysed and assumptions made, LSE appears to approximate RSE.

Furthermore, LSE does offer some additional advantages in comparison to RSE, which can be summarised as follows:

- Data is gathered with reduced H&S risks for a technician
- Data is gathered automatically under normal traffic speeds, without the need for a road closure
- Measured data is collected with a time stamp and GPS location
- Measurement readings are collected continuously, capturing the asphalt's variability along the surveyed section
- Data is digital allowing for incorporation into BIM and PMS systems
- The International Roughness Index (IRI) and surface profiles can be obtained as output from the survey
- LSE reports include the road profile plots and markers noting locations road features

5. Laser based system to measure surface macro-texture

This section details the assessment of 3D-TD as innovative technology against conventional volumetric patch to measure asphalt surface macro-texture.

5.1 Introduction

The 3D-TD is a 3D laser profiler (laser line plus camera) system. The vehicle mounted device (Figure 4) comprises a 2D laser with a 200 mm wide measuring beam, an encoder attached to one of the vehicle wheels to measure distance, GPS and a software program which combines each parameter and builds a 3D profile of the road as it drives longitudinally (Figure 5).

This system enables calculation of Mean Texture Depth (MTD) in accordance with EN13036-1 [42]. It has been designed to be carried out at traffic speed, therefore, it does not require traffic management.

Figure 4 – MATtest vehicle mounted 3D-TD system (courtesy of MATtest Ltd).

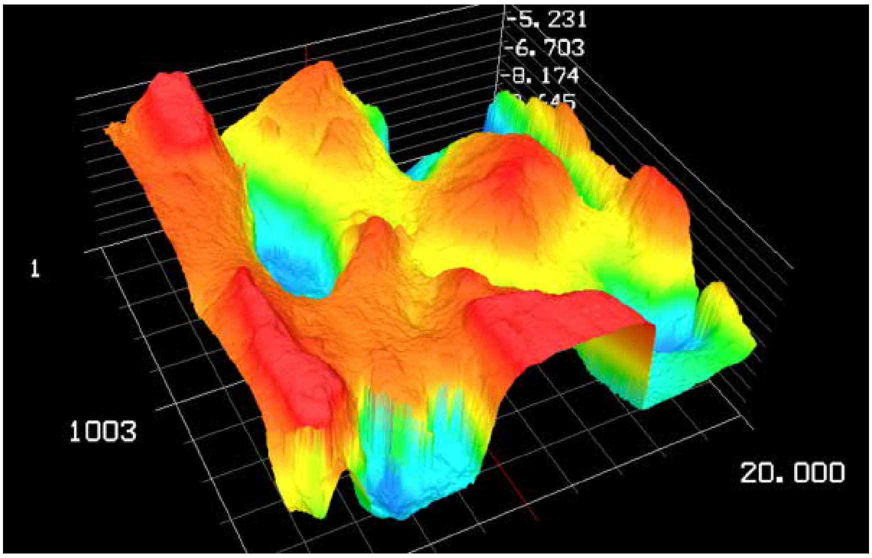


Figure 5 – Example of 3D texture road profile built via MATtest software program [136]**.**

5.2 Data analysis

To compare the 3D-TD system with the volumetric patch, testing data sets include the information from the following sites/surveys:

- M1 Junction 5 (High Friction Surfacing)
- M25 Junction 25 (High Friction Surfacing)
- M25 Junction 28 (High Friction Surfacing)
- M25 Junction 23 (High Friction Surfacing)
- M4 Junction 4 (High Friction Surfacing)
- M4 Junction 4 Heathrow Spur Road (Clause 942 TSCS)
- A76 North of Garleffan (Surfacing complying with Transport Scotland TS 2010)
- A82 Garshake Road (Surfacing complying with Transport Scotland TS 2010)
- M8 Junction 27 Arkleston (Surfacing complying with Transport Scotland TS 2010)
- M8 Junction 29-28 Arkleston (Surfacing complying with Transport Scotland TS 2010)
- M1 Junction 16-19 (Clause 942 TSCS)
- A269 Ninfield Road (Clause 942 TSCS)
- A46 Hobby Horse to Widmerpool (Clause 942 TSCS)

The specification [43] requires the measurement of texture depth (as per EN 13036-1 [59]) to be reported as an average of 10 individual measurements taken at approximately 5 m spacing along a diagonal line across the lane width. The 3D-TD equipment runs along the lane centre at traffic speed, continuously collecting (1 m sample interval) texture measurements. Therefore, a point-to-point comparison of the two methods is not practical for inclusion in this analysis (especially with the 3D-TD being conducted at traffic speed).

The two methods were compared considering the average of a set of 10 volumetric patch measurements with the average of 3D-TD readings over the same length.

Site records were used to match start and end points for each 50 m section for conventional and laser surveys.

For each site and location, the average Mean Texture Depth (MTD) values obtained from 3D-TD and volumetric patch were compared (see Appendix B). The overview of all these data is reported in Figure 26 (see Appendix B).

MTD values measured with 3D-TD closely mirror readings taken using the conventional volumetric patch. The relative difference at the majority of the locations (see Figure 6) is within 7% between the two methods (of the line of equality). 7% is also the average variation of volumetric patch measurements for the analysed sites (see Table 12). All points in Figure 6 fall within 27%, which is also the volumetric patch variation from randomly selected locations within a nominally homogeneous pavement section reported in BS EN 13036-1 [42].

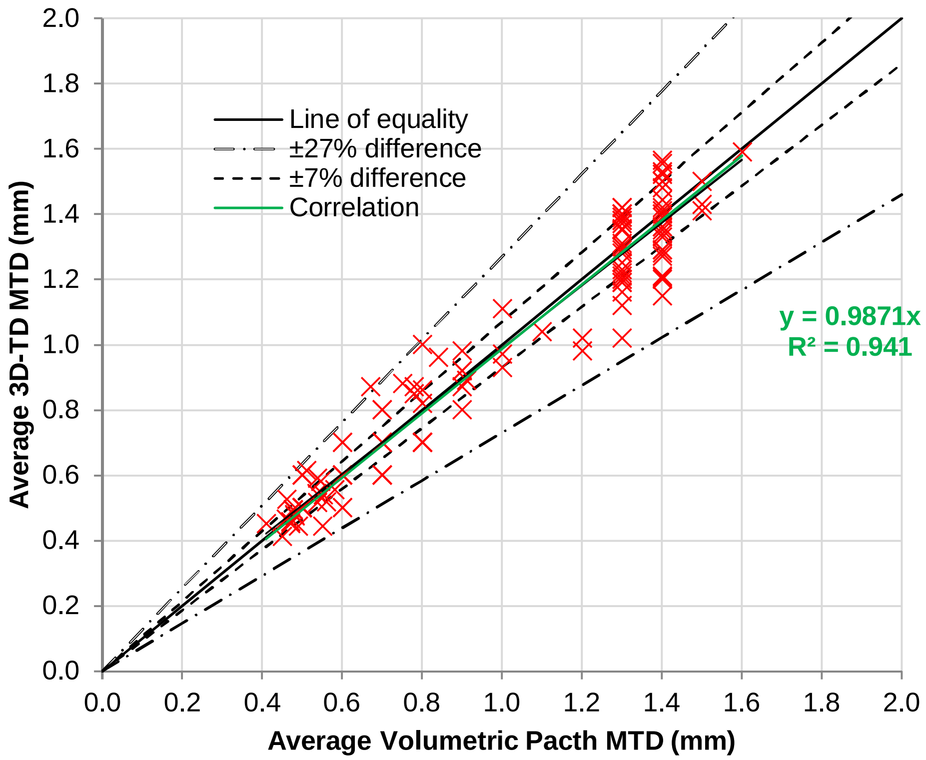


Figure 6 – Summary of 3D-TD *v.* Volumetric Patch measurements

Overall, the correlation with volumetric patch is higher than 94%. Based on the results analysed, it can be stated that 3D-TD approximates to the conventional volumetric patch.

Table 12: Percentage Difference between 3D-TD and Volumetric Patch, together with variations of Volumetric Patch

Site	Absolute Measured difference 3D-TD *v.* Volumetric Patch (%) Site average	Volumetric Patch Variations = SD/Mean
M1 J5	7%	7%
M25 J25	7%	8%
M25 J28	11%	13%
M25 J23	4%	11%
M4 J4	10%	8%
M4 J4 Heathrow Spur Road	8%	3%
A76 North of Garleffan	11%	9%
A82 Garshake Road	11%	10%
M8 Arkleston	7%	6%
M1 J16-J19	6%	4%
A269 Ninfield Road	7%	0%
A46 Hobby Horse to Widmerpool – 14 mm	13%	10%
A46 Hobby Horse to Widmerpool – 10 mm	3%	5%
Total average	**8%**	**7%**

Figure 6 shows that, for texture higher than 1mm, 3D-TD method overall tends to slightly underestimate the readings obtained from the volumetric patch method. A boxplot analysis was carried out to identify a possible correlation with the nominal aggregate size, as reported in Figure 7.

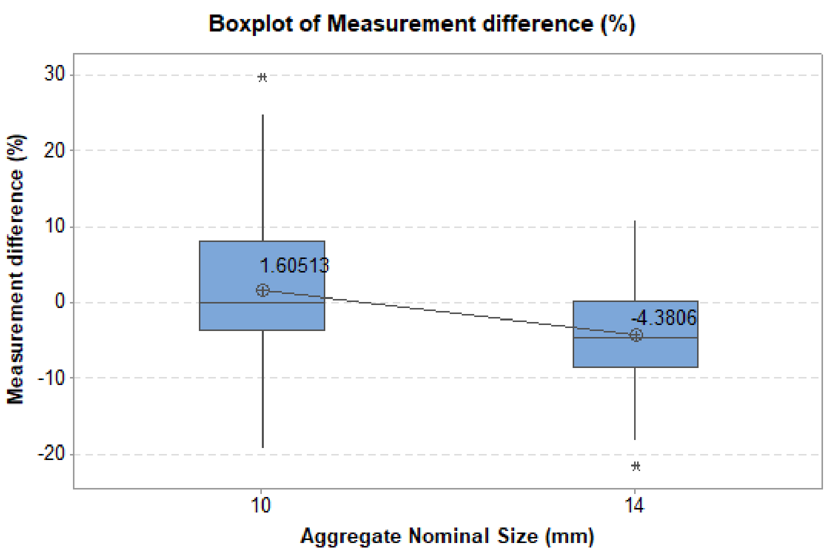


Figure 7 – Influence of aggregate size on the percentage Difference between 3D-TD and Volumetric Patch measurements

Selected analysis undertaken by splitting the data sets on the basis of nominal aggregate size (which will also be linked to texture depth) show that 3D-TD tends to slightly underestimate texture for the 14 mm surfacing. This may be attributed to the 3D reconstruction of laser scanning technique which uses a laser line and a camera at an angle that detects the shape of the line, based on which the depth of the surface is evaluated [11]. Therefore, the laser system, which travels at traffic speed will not always reach the full-depth of surface textures for larger aggregate. Further analysis and a large data set is required to confirm this potential trend.

5.3 Compliance results

Table 12 summarises the average difference between the two methods for each site together with the variations of volumetric patch within the same site.

The absolute difference between the two methods for each site ranges from 3% to 13%, with a total average of 8%. This is comparable with the measured average variation of volumetric patch measurements for the analysed sites (7%). Therefore, 3D-TD outcomes are likely to reach the same conclusion in terms of compliance with specifications (Table 9/3 (08/08) of MCHW Series 900 [43]).

5.4 Repeatability test

To evaluate the repeatability of 3D-TD, a single 97 m length section was tested ten times using the same equipment and the same operator, in the same day (Figure 8).

Considering the average MTD for each run, the repeatability error is 4%.

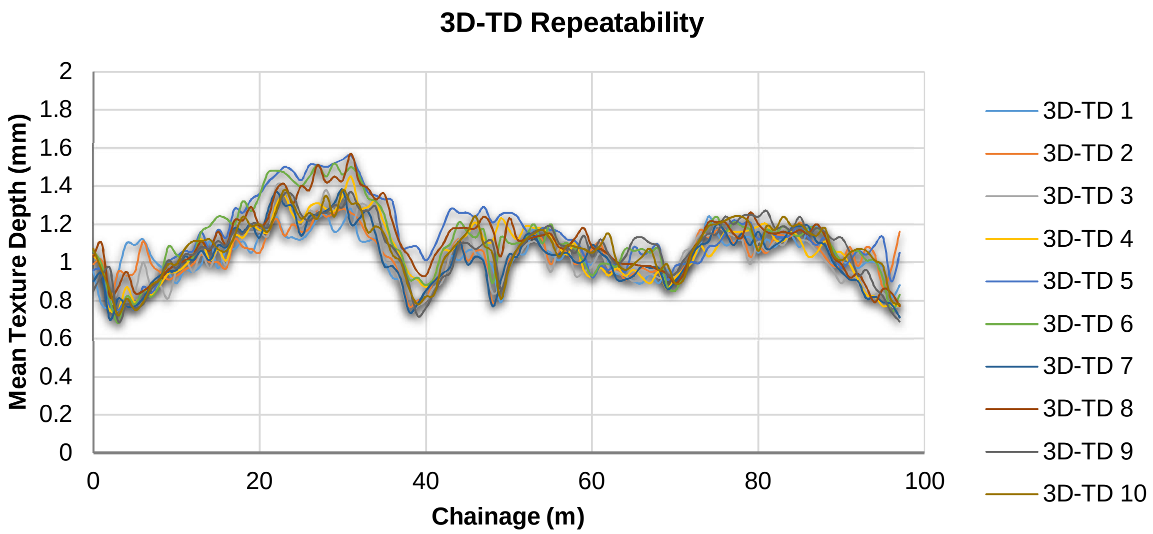


Figure 8 – MATtest 3D-TD repeatability trial results

5.5 Summary of findings

Data sets analysed showed that, for most of the locations, the relative difference between the two methods is comparable to the variations of volumetric patch measurements for the analysed sites. Furthermore, this relative difference between the two methods, in all cases analysed, was lower than the volumetric patch variation from randomly selected locations within a nominally homogeneous pavement section reported in BS EN 13036-1 (27%). The correlation between the 3D-TD and volumetric patch was higher than 94%.

The repeatability trial carried out produced relatively good results for average texture depth. However, a reproducibility study should be considered in future research on 3D-TD technology.

Overall, based on the data sets analysed, 3D-TD laser-scanning technique appears to approximate to conventional volumetric patch.

In addition, 3D-TD offers some additional benefits in comparison to volumetric patch testing:

- Data is gathered with reduced H&S risks for a technician;
- Data is gathered automatically under normal traffic speeds, without the need for a road closure;
- Measured data can be collected with a time stamp and GPS location;
- Measurement can be carried out continuously;
- Data is digital allowing incorporation into BIM and PMS.

6. Contactless system to measure in-situ density

This section details the assessment of PaveScan as innovative technology to measure asphalt in-situ density.

6.1 Introduction

The PaveScan system is a manually propelled Ground Penetrating Radar (GPR) system capable of incorporating up to three sensors to determine the dielectric constant of asphalt concrete [91,141]. PaveScan was developed in 2013 by Geophysical Survey Systems Inc. (GSSI) and Texas Transportation Institute (TTI) as part of the Federal Highway Administration's Strategic Highway Research Program [142].

This system differs from traditional GPR systems used on roads for two main features: (i) typical GPR systems use large antennas (more than 10 kg) while PaveScan system uses small form-factor antennas weighing less than 1 kg; the smaller form-factor simplifies mounting hardware requirements allowing mounting more than one antenna in the same cart; (ii) each GPR antenna contains a processor that implements a sequence of processing steps that results in the output of a dielectric value from each scan of data; the dielectric value is then sent via Ethernet to a computer that collects the dielectric values from each antenna and displays them as the equipment is moved along the paved surface [143].

The complete three-channel system consists of three sensors that are connected to a concentrator box (Figure 9). The developed protocol assumes that the outer GPR sensors are spaced approximately 60 cm from the sensor located at the array centre. The location is monitored by GPS equipment and GPS data is recorded in conjunction with GPR data [141].

PaveScan typically outputs a measurement each 30 cm along the lane travelled, providing roughly 9,000 measurements for each km of surveyed lane, when using the three-channel system [142].

The cart is outfitted with a tablet for data visualization. Data can be collected at a similar rate to paving, enabling an operator to provide real-time feedback of general trends in compaction. The survey data is stored internally and can be exported in '.CSV' files [141].

Figure 9 – Side view of PaveScan cart [141]

6.2 Mode of operation

The procedure used to complete a survey with PaveScan system is summarised as follows [91]:

1. Preparation and equipment start-up prior to testing:
    a. Input of relevant project information
    b. Input of number of sensors used
2. Calibration of equipment prior to testing:
    a. Airwave calibration (Figure 10a)
    b. Metal plate calibration (Figure 10b)
    c. Swerve calibration (Figure 10c)
    d. Survey Wheel calibration

    Calibration in accordance with the above takes around 30 minutes and has to be carried out every time prior using PaveScan [138].
3. Testing. Three survey types for data collection are recommended by GSSI [90,91] (Figure 10d). First, a lane survey to collect data in the middle of a lane; second, a joint survey to collect data along the longitudinal joint; and finally, a shoulder survey is used to collect data near the shoulder or on the opposite of the lane as the joint survey if surveying a multi-lane roadway.
4. Core calibration (Figure 10e). The core calibration can be undertaken in two ways:
    a. 'File playback' – with this method relevant cores (high, mid and low dielectric) are selected after survey.

b. 'Real time' – with this method cores to be extracted are selected during the survey for example in locations relevant to the project.

After having calculated air voids from cores, the correlation law coefficients can be evaluated.

5. Results are converted to air voids estimate.

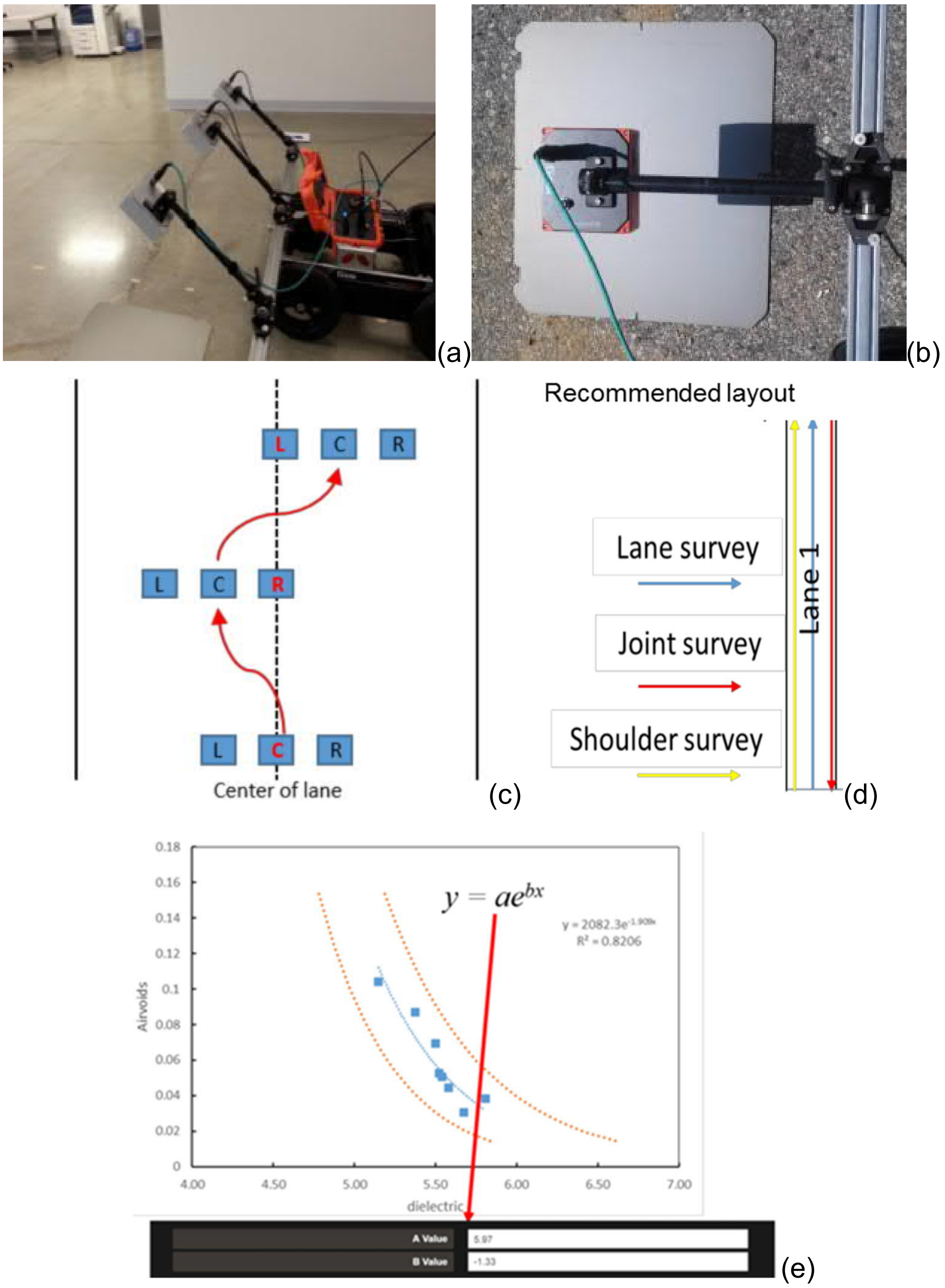


Figure 10 – (a, b, c) Calibration of PaveScan prior testing; (d) Recommended survey layout; (e) Core calibration [91]

6.3 Feedback from trials (US and UK)

After its initial development, PaveScan has been used in several pilot studies in the US [142]. Surveys carried out in Nebraska [144] and Maine [145] in 2016 showed large variations in correlation between asphalt dielectric values measured and the air voids of cores determined via laboratory analysis. An issue of not being able to measure density for very thin layers (less than 25 mm) is reported from the trials [144,145].

In August 2018, this technology has been trialled in the UK. The material tested was Clause 929 AC32 HDM 40/60 base.

During the trial, PaveScan dielectric data were calibrated against non-nuclear gauge (PQI) measurements. In this validation trial, large variations (up to 21%) between the two methods were observed (Figure 11).

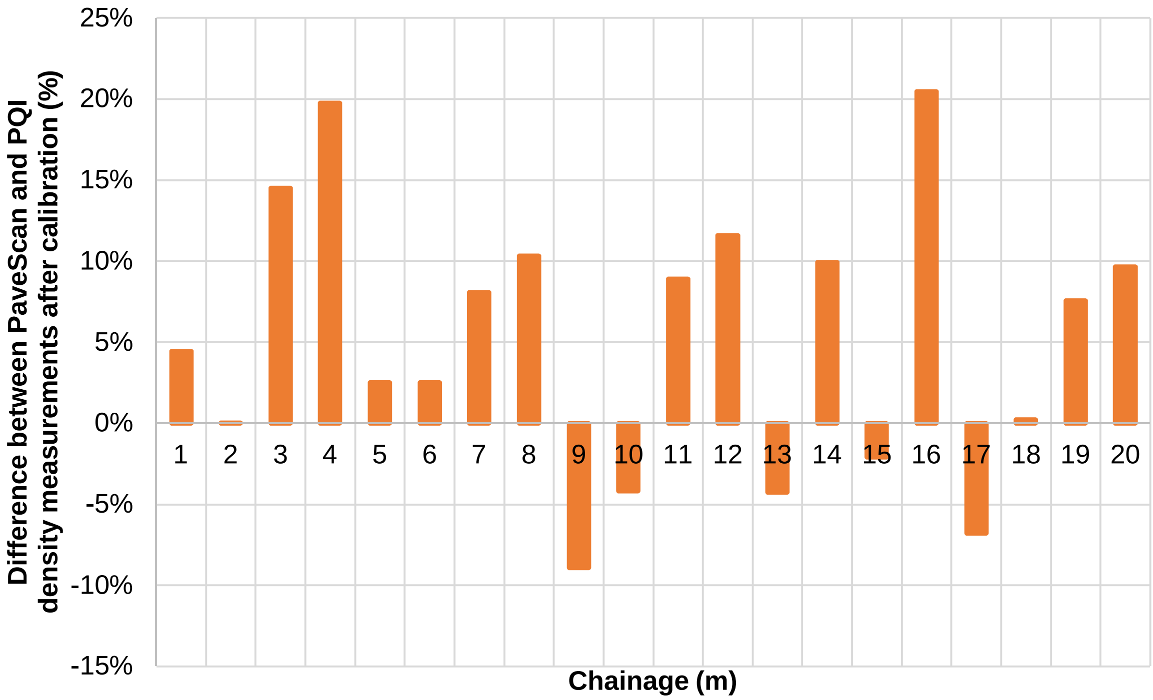


Figure 11 – PaveScan *v.* PQI density

The above trial does not currently support the adoption of this system as a replacement for direct measurement of density. However, its potential is under further investigation by equipment suppliers; including the potential to attach it to asphalt compaction plant.

6.4 Summary of findings

The PaveScan system presents the following potential benefits [142]:

- Once calibrated, it is a rapid method, potentially adaptable to being put on a vehicle;
- Being contactless, it can potentially increase safety if mounted on a vehicle;
- Measurement can be carried out continuously, capturing the asphalt's variability along the surveyed section in comparison to nuclear and non-nuclear density gauges.

Nevertheless, similar to other GPR measurement systems, PaveScan results are affected by water and temperature (see Table 5). However, it is claimed that when used under constant conditions, variations in the dielectric readings could help identifying poor compacted areas and taking positive actions [90].

The tablet battery generally limits PaveScan surveys to 6 hours. This issue could be overcome by implementing a power system when PaveScan is connected to a roller. The main challenge associated with this system is the cumbersome process and requirements for analytical skill to carry out the calibration.

Overall, based on the limited information, trials and datasets available, this system shows potential, but requires further development prior to application for QC/QA.

7. Automated quality monitoring systems

This section describes the review of selected automated technologies which can be potentially used in the UK network to monitor the quality during pavement construction.

7.1 Introduction

To assess the APEX paving record system, Roller (intelligent compaction) system and the PAVE-IR system, the information from the sites/surveys reported in Table 13 were used.

Table 13: Available Automated Systems Datasets

Sites	Paver Laying Record	Roller System	Pave-IR Scanner
M4 Junction 4	✓ (Location Map and Graphs)	✓	✓
A269 Ninfield Road	✓	✓	
A46 Hobby Horse to Widmerpool	✓ (Location Map and Graphs)		
A134 Thetford	✓	✓	
A143 Harleston	✓	✓	
A1066 Garboldisham	✓	✓	
Town Street, Upwell	✓	✓	
London Road, Thetford	✓	✓	
B1146 Quebec Road	✓	✓	
Mill Lane, Repps Rd & High Rd Marham	✓	✓	
Little Plumbstead, Belt Rd	✓	✓	
London Road, Wymondham	✓	✓	
A76 Templeton Rdb to Little Heath	✓	✓ (correlated with PDM)	

The following sections give a brief introduction of each system and a couple of examples of the applications.

7.2 APEX System

The APEX system is an alternative to laying records; facilitated by use of vehicle tracking technology. Individual lorry locations can be tracked from weighbridge to and from the construction sites. Vehicle data and weighbridge load can be automatically uploaded through the suppliers' terminals. Figure 12 shows a screenshot of the tablet version of the APEX interface.

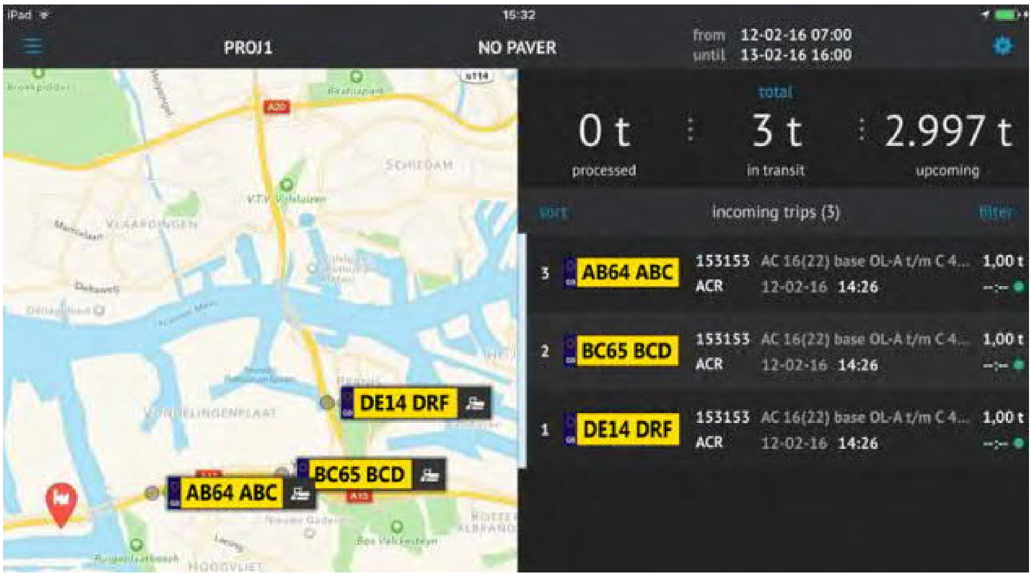
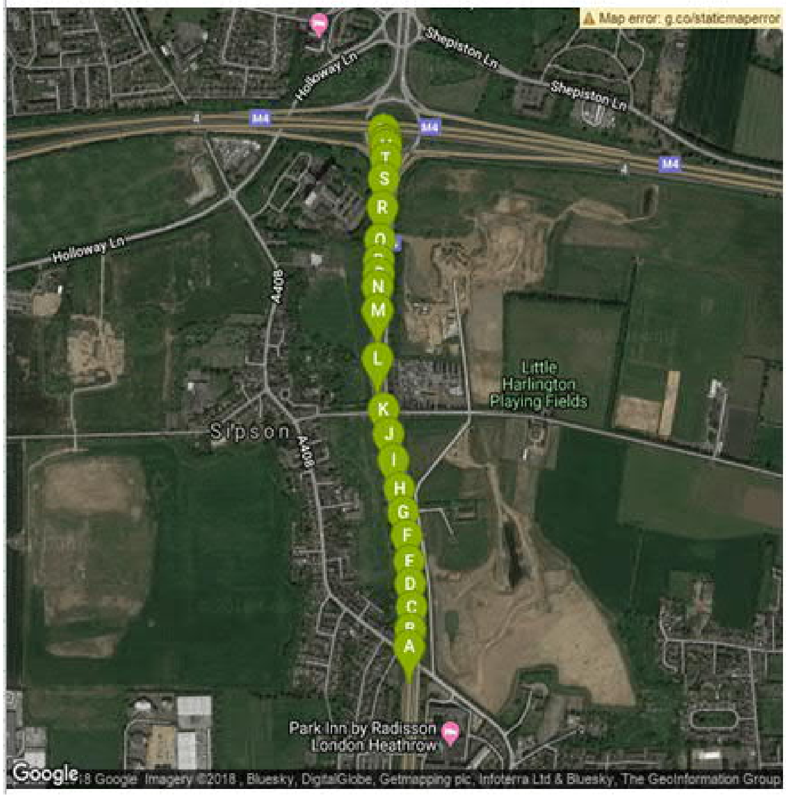


Figure 12 - Screenshot of the APEX Interface [146]

Similar to other systems, APEX can provide laying records in '.csv' format including paver registration, material, tonnage, load time and time at paver, GPS coordinates, material temperatures, rain/humidity, air temperatures and wind speeds. Plotting the pavers on a map using the GPS locations, it provides an intuitive map for every load of material at its destination road sections, as shown in Figure 13. The temperatures, time from dispatch to unload and weather conditions can be graphically represented, as shown in Figure 14.

These types of systems can be used to highlight any delay in the delivery and provide real-time locations and loads and weather conditions to assist onsite planning.

Location Map



Map Legend

A = OO06JKT
B = EU16GHB
C = G15WAL
D = KW13GVX
E = KP63JHU
F = P411LCH
G = GL65GAL
H = TA67MAC
I = OO08JKT
J = PK51JAS
K = EU16GHB
L = OO06JKT
M = G15WAL
N = KW13GVX
O = KP63JHU
P = P411LCH
Q = OO08JKT
R = KY66LFX
S = GL65GAL
T = PK51JAS
U = EU63EZO
V = EU65WXP
W = K19JKP
X = EU13VHT
Y = W14MPC
Z =

Figure 13 – Example of APEX Load Location Map

Graphs

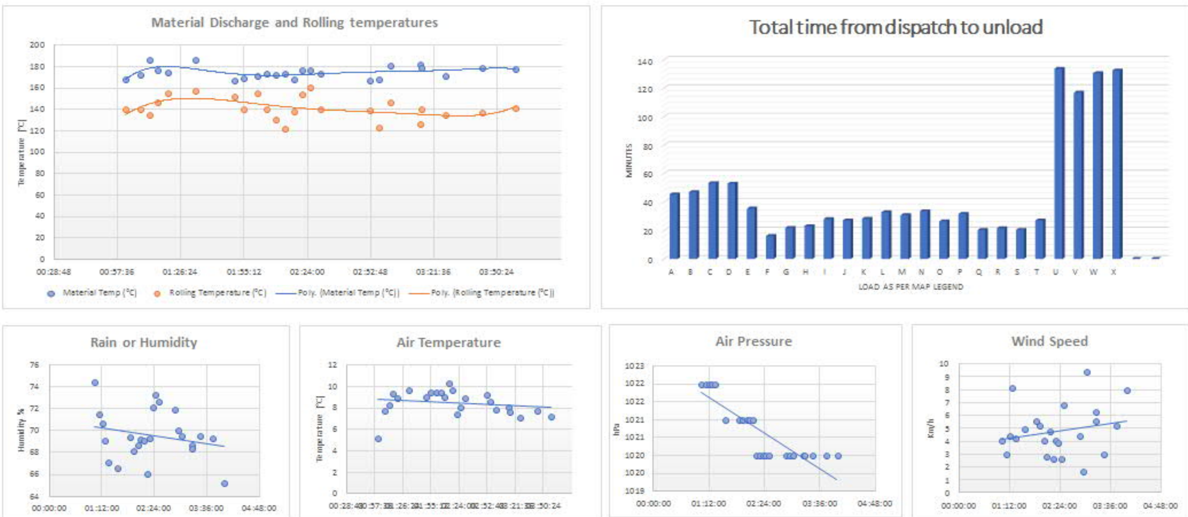


Figure 14 – Examples of APEX Graphs

7.3 PAVE-IR Scanner System

The PAVE-IR scanner system consists of a set of three infrared temperature sensors (two at auger and one at hopper), a GPS locator and a weather station for wind speed, ambient temperature, air pressure and humidity and an on-board display. The data is automatically uploaded to a central server.

Report output comprises the thermal profile (Figure 15), temperature plot (Figure 16), paver stops graph (Figure 17) and the weather conditions. In the thermal profile, the x-axis shows the distance along the travel path of the paver. The y-axis shows the distance along the paver screed. The black colour indicates a cold temperature. The mean temperature from the three sensors is used to determine the material delivery temperature.

The temperature patterns help to identify cold spots and, therefore, have potential to be used to inform operational decisions on:

- Locations that need urgent compaction
- Need for cutting joint
- Provision of feedback for continuous improvement

It provides a continuous indicator of progress relative to temperature, such as paver stops. Combined with other information, such as the waiting time from APEX, the roller temperatures from roller systems and weather conditions, it helps to demonstrate if, where and why the cold spots have led to unfavourable outcomes, and hence, enables the operators to take positive actions to avoid cold spots and/or to mitigate the negative impact. Although the current thermal cameras on the market can provide the temperature profiles on the asphalt mat, the PAVE-IR scanner system offers the advantages of profiling the entire pavement width, collecting, displaying, saving, uploading and analysing temperature readings while in operation and providing continuous thermal profiles with integrated GPS locations and environmental conditions. Essentially, the main advantage is being an integrated system. Meanwhile, the temperatures by remote methods are only indicators of the rolling temperatures and should not be used as a compliance measure.

This information can be used in identifying cold mat areas for subsequent core density testing which would complement the current QA/QC procedure.

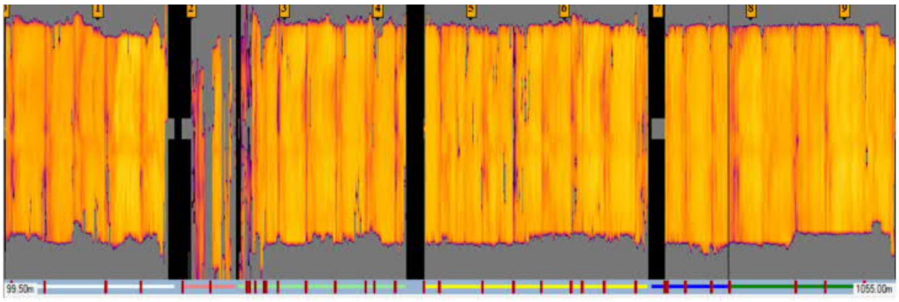


Figure 15 Example of PAVE-IR Thermal Profile.

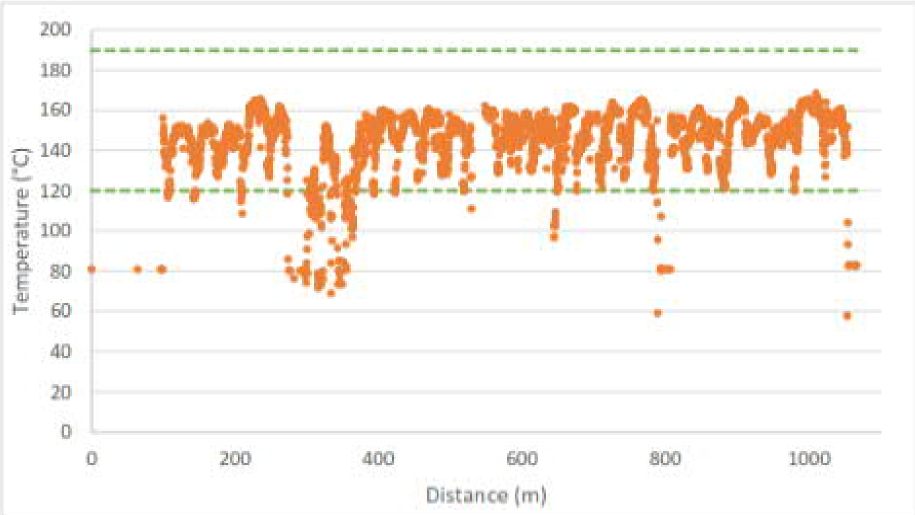


Figure 16 Example of PAVE-IR Temperature Plot.

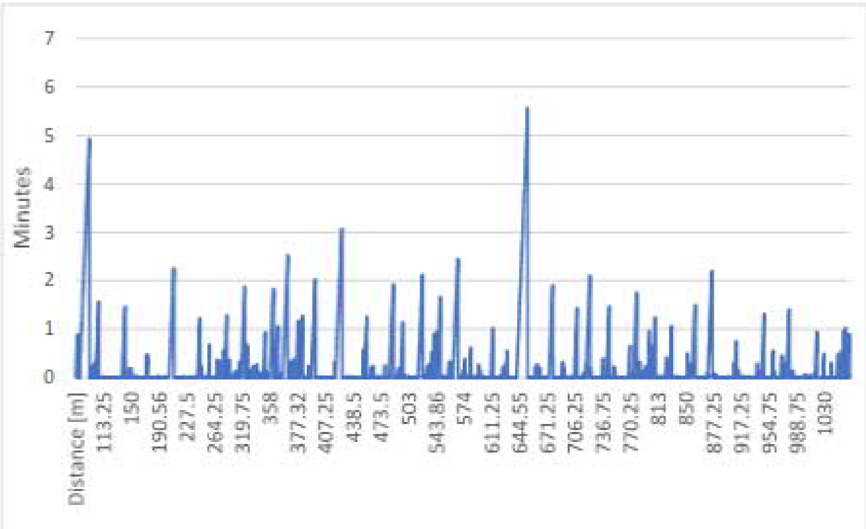


Figure 17 Example of PAVE-IR Paver Stops

7.4 Roller System

The system reviewed as part of this project incorporates a GPS sensor, an infrared temperature sensor and an on-board display for roller passes and temperatures. The digital information can be automatically uploaded to a central server for real-time monitoring and for potential incorporation into the asset management systems at a later stage. Figure 18 shows a typical screenshot of the roller analysis software interface. In this example, the number of roller passes is colour-coded and shown on a GPS-coordinated system. The roller static passes and the maximum rolling temperature are included in the final compaction report (Figure 19 and Figure 20).

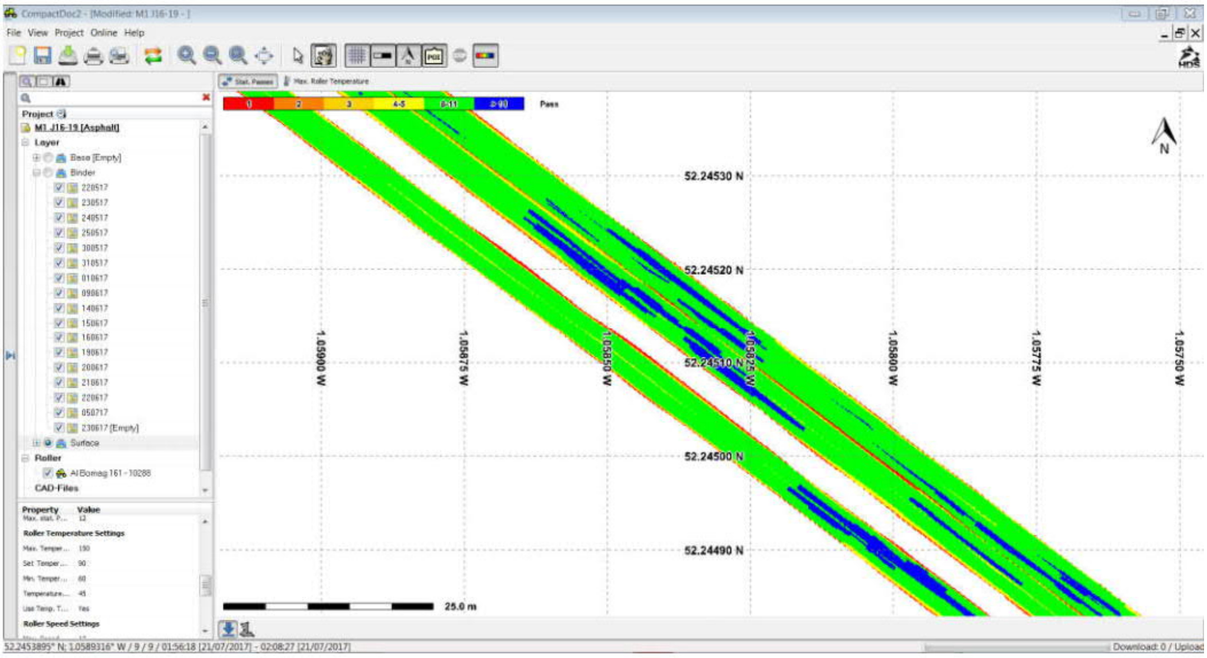


Figure 18 - Screenshot of typical Roller Analysis Software [146]

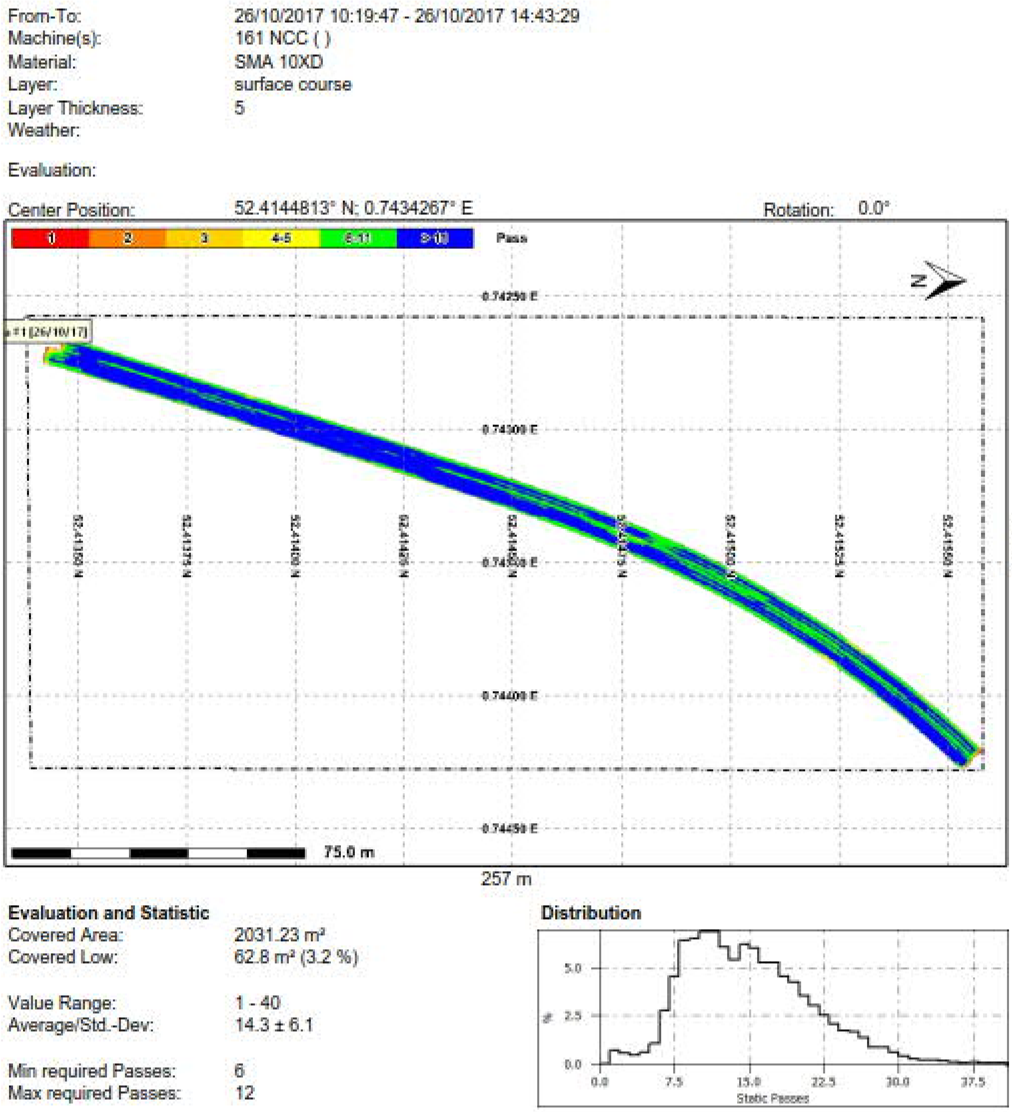


Figure 19 – Example of Roller Static Passes

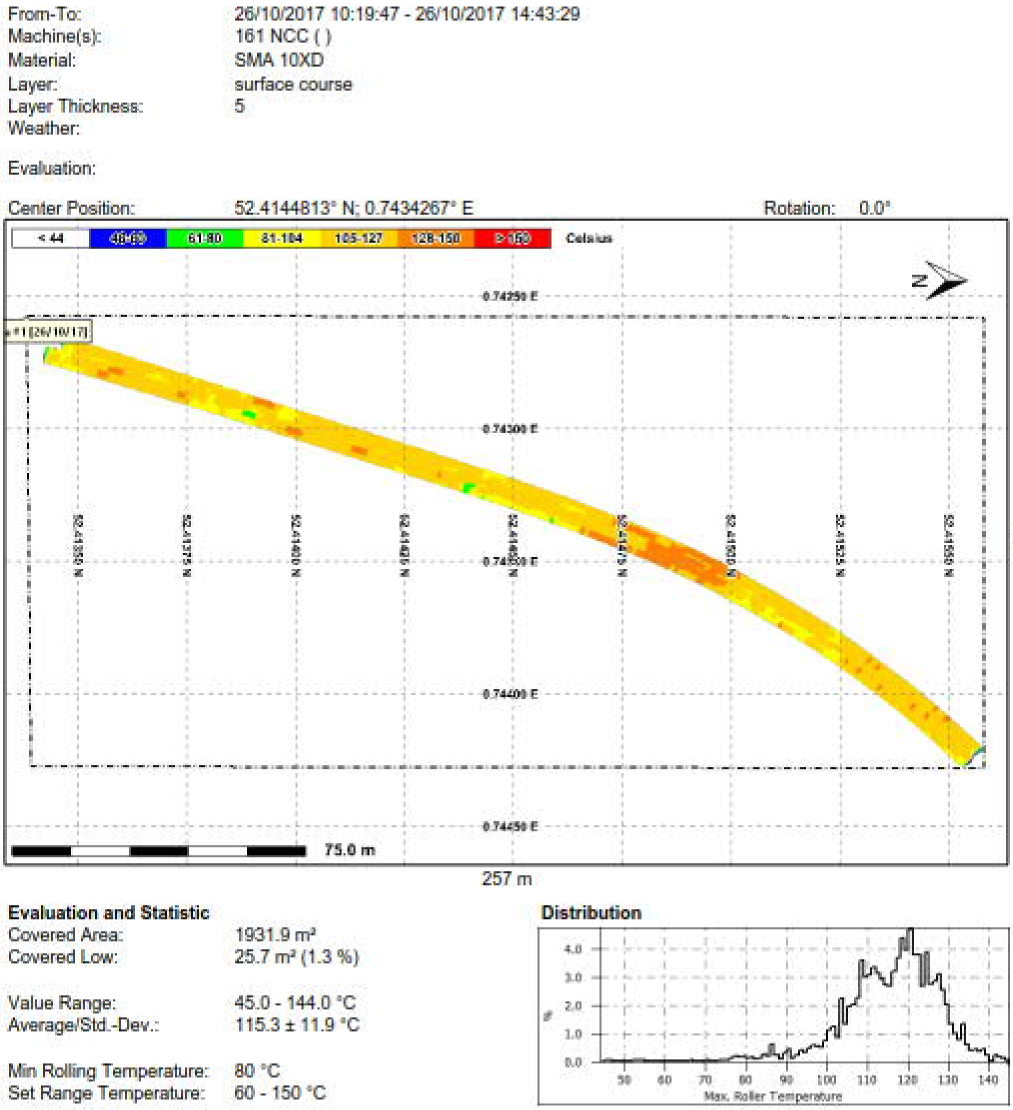


Figure 20 – Example of Maximum Rolling Temperature

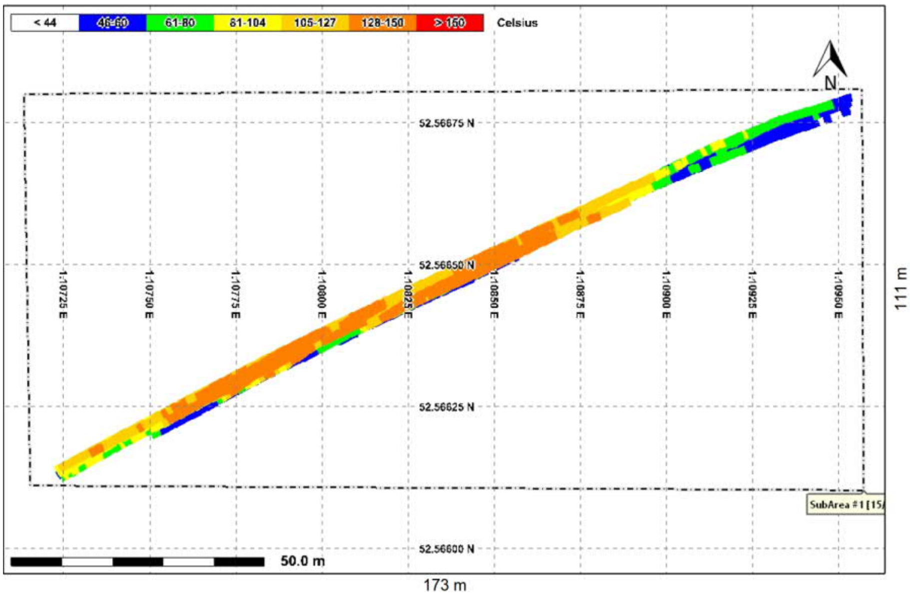


Figure 21 – Example of Maximum Rolling Temperature – Cool Material

Figure 21 is an example showing the maximum rolling temperature at a Norfolk Local Authority higher scheme. The asphalt surfacing requires a minimum rolling temperature of 80°C, which is in yellow in the colour scale. The plot highlights the cool material near the end of the section, dictated by the blue and green colour. Assessment of the site records confirmed the material was delayed on site.

7.5 Asset Management System (data collection at construction stage)

These automated systems can be used as quality control measures during pavement construction. Subject to further study on the correlations with the existing performance criteria, they may present themselves as quality assurance tools for compliance. Moreover, they could benefit the asset management with automated data collection, recording and uploading. The automated data collection provides highly accurate and comprehensive data with minimal post-processing. On the contrary, manual data collection would require considerably more time and cost in walking / windshield surveys, manual recording, back-tracking the construction information and manual inputting onto the asset management platform. Plus, the manual data collection bears a greater chance for human errors.

Roller data can be integrated into the asset management interface such as Horizons. Figure 22 shows an intuitive road map overlaid with colour-coded roller passes in dots.

This study is at an early stage. To materialise an integrated asset management system with the automated construction data, is it essential to understand:

- To what level of detail would it be practical and beneficial for asset management, considering the large data sets?
- How to manage and make most of the data sets?

The above are areas for further consideration.

Figure 22 Horizons – Example of Roller Passes

7.6 Summary of Findings

The automated systems provide continuous large data sets from the automated data recording during construction, which is likely to be more efficient and accurate than manual recording. The real-time monitoring can provide access to the information for suppliers, laying teams and project managers, which could help to inform operational decisions. The comprehensive information can also assist in procedures managing quality. However, this is dependent on how the data sets are used.

Meanwhile, the following points would also need consideration.

- Systems do not currently collect certain asset data, such as cover locations and utilities. This is considered of more importance on local roads than strategic networks.
- The systems are considered more suitable and beneficial for large scale works, but less so for local repairs, such as trench repairs and pothole reinstatements, considering the nature and scale of the works.
- The correlation between the compaction passes and the current performance criteria (e.g. density and air voids) is dependent on more variables (see Section 3.4).
- The temperatures by remote methods are only indicators of the rolling temperatures and need calibration with a referencing temperature probe (see Section 3.6).
- The automated systems use GPS coordinates whilst most traditional tests/records tend to use local chainages and OS grid references. Since the automated systems will not replace the traditional methods completely in the short term, cross-referenced locations would help in the data interpretation and correlation.
- Training is required to analyse and assess the output information. Considering the amount of data produced, a protocol for standardised data exchange would be useful to keep data manageable and consistent between projects.
- The automated systems enhance data recording and management, can help to inform operational decisions and assist with investigations and prevention. They may be considered suitable as QC measures to support existing performance tests. However, they have limited application unless reliable correlation with performance parameter can be identified. Overall, the automated systems are not considered technology ready for compliance purposes.

8. Discussion and Conclusions

This report details the work undertaken under Sub-Task 2: Evaluation of QC and QA Test Methods. It is part of a wide Collaborative Research Project commissioned by Highways England (HE), Mineral Products Association (MPA) and Eurobitume UK.

Sub-Task 2 explored the possibility of incorporating recent technological advancements and automation in quality monitoring equipment, as an alternative to the conventional testing and monitoring of asphalt pavement. A driver for this review was that the conventional test methods inherently carry safety risks for site technicians who undertake the works on foot. The use of automated technologies currently available to the construction industry could remove and/or mitigate the exposure of site technicians.

The following objectives were identified:

O1. Review conventional test methods for all the areas considered

O2. Review innovative test methods for all the areas considered

O3. Selection of technologies which can be used in the UK

O4. Comparison and validation of the selected technologies with the conventional test methods, for the following areas: asphalt surface regularity, asphalt surface macro-texture and in-situ density

O5. Setting of acceptance criteria for QA

O6. Propose recommendations for future specifications

To achieve these objectives, an initial review of conventional and innovative technologies was carried out for: asphalt surface regularity, asphalt surface macro-texture, asphalt in-situ density, intelligent compaction, asphalt pavement distress and asphalt temperature.

Innovative technologies were selected for further assessment based on automation level, measurement speed, experience on the strategic road network and availability in the UK. The relevant suppliers for the selected technologies were engaged and site trials planned to assess the selected technologies against conventional methods through validation trials.

The innovative technologies/systems identified for further analysis were the Laser Straight Edge (LSE, measuring surface regularity), the 3D-TD (measuring texture depth), the PaveScan (measuring in-situ density), the APEX system (optimising efficiency of paving process), PAVE-IR (system producing laying records) and roller system (Intelligent Compaction system).

Data sets from several schemes in the UK conducted on motorways, trunk roads and local roads, including surface regularity, surface macro-texture and in-situ density, have been analysed for both conventional and innovative systems.

For the measurement of surface regularity the Rolling Straight Edge (RSE) is the industry standard method. The use of laser surveys to measure pavement regularity can output the total number of irregularities above 4 mm, 7 mm and 10 mm for a given section (75 m or 300 m), as specified in current MCHW Series 700 Table 7/2. Based on the data analysed, the automated LSE approximates to RSE, although more work needs to be done to build up the evidence base for any future change to the contractual base line of the RSE.

Volumetric patch is a standard method to measure surface texture depth, which is currently referenced in the MCHW. The laser surveys (3D-TD) can provide the average MTD for a 50 m section every 250 m, as specified in current MCHW Series 900 albeit on a linear direction (as opposed to diagonally within lane). Results analysed show that 3D-TD has relatively good repeatability and a good correlation with volumetric patch (higher than 94%). The relative difference between the two methods was always lower than the volumetric patch variation, from randomly selected locations within a nominally homogeneous pavement section reported in BS EN 13036-1 (27%). Therefore, on the basis of this work it is considered that 3D-TD approximates to the volumetric patch.

Overall, both LSE and 3D-TD systems present clear advantages in relation with conventional methods: the risk for a technician is reduced because the surveys are conducted under traffic speed without the need for road closure; measurements are carried out continuously and stored digitally with additional information for incorporation into BIM and PMS.

PaveScan is one of several techniques proposed as an alternative method for measuring in-situ density. These systems may be adapted to use on a vehicle; therefore, they have the potential to increase survey safety and automation. However, this review found large variations in this system when compared against other methods such as core density and PQI. Therefore, further research is needed to demonstrate the suitability of this system for QC/QA purposes.

The automated APEX, PAVE-IR and Roller systems provide continuous streams of large datasets automatically captured during the construction. The real-time monitoring can facilitate operational decisions. The comprehensive information also helps in the follow-up investigations for any non-compliance cause identification and/or prevention purposes. Overall, these systems are considered suitable as QC measures to improve construction quality and efficiency. However, there are a few issues to be implemented before they may be considered adequate as compliance tool. Currently human interventions are required to supervise and to avoid any false readings, such as checking the cold spots for ironworks.

9. Recommendations for future work

This research has demonstrated that the repeatability of LSE and 3D-TD systems appear comparable to the manual measurement systems. Areas for further investigation include:

- Reproducibility study, linked to development of standardisation and consideration of alternative measure e.g. IRI to reflect road user experience and comfort (rideability).
- Laser survey to measure surface regularity and surface macro-texture should be conducted at sample intervals of 1 m or lower.
- The LSE and 3D-TD systems are useful supplementary methods to the contractual requirements for Highways England works. However, at the moment not enough information is available to recommend the replacement of current QC/QA testing of asphalt pavement. In this context, it is recommended to consider LSE and 3D-TD as screening tests whilst the RSE and volumetric patch are still the definitive methods in cases of dispute.
- Modification of PaveScan system to be used on a vehicle.

Considering the potential benefits from the automated quality monitoring systems, it is recommended that future road resurfacing scheme could specify a parallel set of tests during construction (i.e. using both conventional and automated testing). This will allow further verification of the repeatability of these two different systems and an opportunity support future revision of specification requirements.

Acknowledgements

We gratefully acknowledge Highways England (HE), Mineral Products Association (MPA) and Eurobitume UK for providing the funding towards this collaborative research.

We greatly appreciate the support received from MATtest for providing the information and for their permission to use the datasets necessary to undertake our independent analysis. Finally, we thank Norfolk, Hanson Contracting, Tarmac, FM Conway and Transport Scotland for the permission to use their datasets.

References

[1] Highways England, Assessment Procedure for “Innovative” techniques and materials, 2017.

[2] A. Marradi, Harmonization in pavement smoothness rating of new and old pavements, Copenhagen, Denmark, 2013.

[3] ASTM E950/950M-09, Standard Test Method for Measuring Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference, 2009. doi:10.1520/E0950.

[4] ASTM E2133 − 03, Standard Test Method for Using a Rolling Inclinometer to Measure Longitudinal and Transverse Profiles of a Traveled Surface, 2013. doi:10.1520/E2133-03R09.2.

[5] ASTM E1364 − 95, Standard Test Method for Measuring Road Roughness by Static Level Method, 2017. doi:10.1520/E1364-95R05.2.

[6] ASTM E1215 − 93, Standard Specification for Trailers Used for Measuring Vehicular Response to Road Roughness, 2017. doi:10.1520/D6064-11R15.2.

[7] BS EN 13036-6, Road and airfield surface characteristics — Test methods — Part 6: Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges, 2008.

[8] BSI BS EN ISO 13473-1, Characterization of pavement texture by use of surface profiles - Part 1: Determination of Mean Profile Depth, 2004.

[9] MCHW, Volume 1 Series 700 Road Pavements - General, 2016.

[10] BS EN 13036-7, Road and airfield surface characteristics — Test methods — Part 7: Irregularity measurement of pavement courses — The straightedge test, 2003.

[11] T.B.J. Coenen, A. Golroo, A review on automated pavement distress detection methods, Cogent Eng. 4 (2017) 1–23. doi:10.1080/23311916.2017.1374822.

[12] B. Worel, B. Chadbourn, R. Strommen, MnROAD Automated Laser Profile System “ ALPS ,” 2003.

[13] R.C. Sohaney, Pavement Texture Evaluation and Relationships to Rolling Resistance at MnROAD, 2013.

[14] Construction Project Administration Manual, Testing and Correcting Asphalt Pavement Surface Deficiencies, 2017.

[15] Http://petsch.cnc.net/web/Runway/RunwayStraighEdge.htm, Precision Straight Edges for Checking Airport Pavement Smoothness, (2009).

[16] Ministry of Defence, Specification 033 - Pavement Quality Concrete for Airfields, 2017.

[17] M.W. Sayers, S.M. Karamihas, The little book of profiling - Basic Information about Measuring and Interpreting Road Profiles, 1998.

[18] P. Tang, D. Huber, B. Akinci, Characterization of Laser Scanners and Algorithms for Detecting Flatness Defects on Concrete Surfaces, J. Comput. Civ. Eng. 25 (2011) 31–42. doi:10.1016/j.csse.2015.06.002.

[19] UKAS, Measurement of Surface Regularity of Road Pavement Surfaces using the Rolling Straight Edge – Requirements for Calibration and Performance Checks, 2008.

[20] Promat (HK) Limited, Rolling Straight Edge, (2018). http://www.promat.hk/detail.asp?catid=64109&subcatid=45387&pdtid=778146.

[21] G. Morrow, A. Francis, S.B. Costello, R.C.M. Dunn, Comparison of Roughness Calibration Equipment - with a View to Increased Confidence in Network Level Data, (2004).

[22] G. Morrow, Comparison of Roughness Measuring Instruments, University of Auckland, 2006.

[23] H. Ceylan, R.F. Steffes, K. Gopalakrishnan, S. Kim, S. Yang, Development and Evaluation of a Portable Device for Measuring Curling and Warping in Concrete Pavements, 2016.

[24] M. a. Cundill, The MERLIN Low-Cost Road Roughness Measuring Machine, in: Res. Rep. 301, Transp. Road Res. Lab., Berkshire, United Kingdom, 1991: pp. 1–25.

[25] H. Wang, Road Profiler Performance Evaluation and Accuracy Criteria Analysis, Virginia Polytechnic Institute and State University, 2006.

[26] DCL, Z-250 Reference Profiler User's Guide, New Zeland, 2004.

[27] T.F. Henning, S.B. Costello, R.C. Dunn, C.C. Parkman, G. Hart, The Establishment of a Long-Term Pavement Performance Study on the New Zealand State Highway Network, Road Transp. Res. 13 (2004) 17–32.

[28] D.N. Brown, Measuring Pavement Condition Data for the Establishment of a Long-Term Pavement Performance Study on New Zealand Roads, (n.d.) 1–23.

[29] ARRB Group, Walking Profiler G3, (2015). https://www.arrb.com.au/Equipment-services/Walking-Profiler-G3.aspx?ForeignLanguage=3.

[30] A. Shah, J. Zhong, J. Ly, Adopting smartphone technology to supplement road asset performance monitoring, in: 17th AAPA Int. Flex. Pavement Conf., 2017.

[31] Dynatest, Dynatest 5051 Mark III/IV RSP Road Surface Profiler, (2013).

[32] Dynatest, Dynatest Model 5051 Mk IV – Portable Road Surface Profiler (RSP) - Quotation, (2017).

[33] https://www.dynatest.com/rsp-mk-iv, Road Surface Profiler (RSP) MK_IV, (2017) 1–2.

https://www.dynatest.com/rsp-mk-iv.

[34] J. Chang, Y. Su, T. Huang, S. Kang, S. Hsieh, Measurement of the International Roughness Index (IRI) Using an Autonomous Robot (P3-AT), in: 26th Int. Symp. Autom. Robot. Constr., 2009: pp. 325–331.

[35] MATtest Southern Ltd, Surface regularity, (2018) 1–3. http://mattestsouth.co.uk.

[36] MATtest Southern Ltd, Report to determine and compare Surface Regularity using the Laser Straight Edge and Rolling Straight Edge in accordance with SHW 702.5, 2017.

[37] MATtest Southern Ltd, Report to determine and compare traditional testing methods and new automated systems proposed by Mattest/HDS and Aggregate Industries, 2017.

[38] BS EN 13036-7:2003, Road and airfield surface characteristics — Test methods — Part 7: Irregularity measurement of pavement courses — The straightedge test, 2003.

[39] AUSTROADS BS.A.65, BS.A.65 Roughness Guidelines Notes - Notes on Technology Exchange Workshop - Validation of Roughness Measurements, 1999.

[40] AG:PT/T450, Commentary to AG:PT/T450 - Determination of the International Roughness Index (IRI) using ARRB walking profiler, 2007.

[41] D.I. Hanson, B.D. Prowell, Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements, 2004. doi:10.3141/1929-11.

[42] BS EN 13036-1, Road and airfield surface characteristics - Test methods - Part 1 : Measurement of pavement surface macrotexture depth using a volumetric patch technique, 2010.

[43] MCHW, Volume 1 Series 900 Road Pavements - Bituminous Bound Materials, 2009.

[44] J. Laurent, J.F. Hébert, M. Talbot, Using full lane 3d road texture data for the automated detection of sealed cracks , bleeding and raveling, in: World Conf. Pavement Asset Manag. WCPAM, Milan, Italy, 2017.

[45] Highway Department UK, Guidance Notes on Road Testing, 1989.

[46] P.O. Docherty, P. Mortimer, W. Infrastructure, Chip seal design using high speed data, 3 (2006) 1–16.

[47] P. Millar, D. Woodward, Ulster University Photogrammetric Method of Highway Surface Recovery and 3D Modelling (UUTex3D), 2017.

[48] E.T. Cackler, Evaluation of U. S. and European Concrete Pavement Noise Reduction Methods, 2006.

[49] R. Sohaney, R. Rasmussen, a Seybert, P. Donavan, New ISO Test Track Specification for Measuring Tire and Vehicle Noise, Sound Vib. (2012) 9–14.

http://www.sandv.com/downloads/1208soha.pdf.

[50] R.Y. Kim, E. Jones, Development of a Testing System for Asphalt Surface Treatments, North Carolina State University, 2015.

[51] J.J. Henry, Determination of the international Friction Index Using the Circular Track Meter and the Dynamic Friction Tester, in: SURF World Road Assoc., 2000.

[52] W.D.M. Limited, TM2 Surface Texture Measurement, (2018). https://www.wdm.co.uk/equipment/equipment-tm2.

[53] W.D.M. Limited, TM2 – Texture Meter, 2018.

[54] D. Holloway, Calibration of laser devices used for the measurement of pavement surface texture: accuracy of pavement texture measurement, in: 3rd Int. Surf. Frict. Conf. Safer Road Surfaces, Saving Lives, Gold Coast, Australia, 2011: pp. 1–9.

[55] MAIN ROADS Western Australia, Surface Texture Depth Stationary Laser Profilometer method, 2012.

[56] Pavimetrics Systems Inc, LCMS - 3D road scanning and texture, 2017.

[57] P. Cenek, N.J. Jamieson, Sensitivity of In-Service Skid Resistance Performance of Chipseal Surfaces to Aggregate and Texture Characteristics, in: 1st Int. Conf. Surf. Frict., 2005: pp. 1–4.

[58] MATtest Southern Ltd, Report to determine and compare the difference of the Mean Texture Depth using the 3DTD Laser device and sand patch method reported in accordance with SHW921 table 9/3, 2017.

[59] BS EN 13036-1:2010, Road and airfield surface characteristics — Test methods — Part 1: Measurement of pavement surface macrotexture depth using a volumetric patch technique, 2010.

[60] BS ISO 13473-3:2002, Characterization of pavement texture by use of surface profiles - part 3: Specification and classification of profilometers, 2002.

[61] AECOM, Improving Durability TSCS – Measuring Asphalt Density - Literature Review, Project No: 60484596, 2016.

[62] BS EN 12697-8, Bituminous mixtures — Test methods for hot mix asphalt — Part 8: Determination of void characteristics of bituminous specimens, 2003. doi:10.3141/2127-15.

[63] BS EN 12697-6, Bituminous mixtures - Test methods for hot mix asphalt - Part 6: Determination of bulk density of bituminous specimens, 2012.

[64] BS EN 12697-5, Bituminous mixtures — Test methods for hot mix asphalt — Part 5: Determination of the maximum density, 2012. doi:10.3141/2127-15.

[65] R. Schmitt, C. Rao, H.L. Von Quintus, Non-Nuclear Density Testing Devices and Systems to

Evaluate In-Place Asphalt Pavement Density, 2006.

[66] R.L. Schmitt, A. Faheem, I. Al-Qadi, Investigation of a Non-Destructive System to Evaluate Critical Properties of Asphalt, 2013.

[67] P. Romero, Evaluation of Non-Nuclear Gauges to Measure Density of Hot-Mix Asphalt Pavements Prepared, The University of Utah, 2002.

[68] Troxler Electronic Laboratories Inc, PaveTrackerTM Plus Electromagnetic Sensing Device for Asphalt Quality Control, (2013) 1–4.

[69] Troxler Electronic Laboratories Inc, Troxler PaveTracker 2701-B Non-Nuclear Device for Asphalt Quality Control Measurements, (2015). www.troxlerlabs.com.

[70] Z. Leng, Prediction of In-situ Asphalt Mixture Density Using Ground Penetrating Radar: Theoretical Development and Field Verification, University of Illinois Urbana-Champaign, 2011.

[71] I.L. Al-Qadi, Z. Leng, A. Larkin, In-Place Hot Mix Asphalt Density Estimation Using Ground Penetrating Radar, Federal Aviation Administration, 2011.

[72] C. Fauchard, B. Beaucamp, L. Laguerre, Non-destructive assessment of hot mix asphalt compaction/density with a step-frequency radar: case study on a newly paved road, Near Surf. Geophys. 13 (2015) 289–297. doi:10.3997/1873-0604.2015009.

[73] T. Scullion, S. Sebesta, D. Rich, W. Liu, Field evaluation of new technologies for measuring pavement quality, The Texas A&M University System, 2006.

[74] F. Zhou, G. Das, T. Scullion, S. Hu, T.I. Office, RAP Stockpile Managemetn and Processing in Texas: State of the Practice and Proposed Guidelines, Austin, 2010.

[75] M. Remily, Understanding & Troubleshooting compaction problems related to testing and materials, in: Adv. Pavers Work., 2014.

[76] TransTech Systems Inc., Pavement Quality Indicator TM Model 301 Operator ’ s Handbook, (2000) 1–36. http://www.transtechsys.com.

[77] R.A. Sovik, R.N. Hosterman, G.. Moross, Paving material analyzer system and method, US 6,803,771 B2, 2014. doi:10.1016/j.(73).

[78] TransTech Systems Inc., Pavement Quality Indicator TM Model 380 Operator ’ s Handbook, 2016.

[79] H. Ziari, B.A. Izadi, H. Divandary, Field Evaluation of Nondestructive Tests in Measuring the Pavement Layers Density, J. Appl. Sci. 10 (2010) 3091–3097.

[80] K. Kabassi, T. Bode, Z. Zhuang, Y. Cho, H. Im, Non Nuclear Method for HMA density measurements, in: 47th ASC Annu. Int. Conf. Proc., 2011.

[81] J.C. Ashlock, R.C. Williams, H.D. Lee, S. Lin, H. Kim, J. Nash, Assessment of Nondestructive

Testing Technologies for Quality Control/Quality Assurance of Asphalt Mixtures, 2015.

[82] R.J. Sztukiewicz, Application of ultrasonic methods in asphalt concrete testing, Ultrasonics. 29 (1991) 5–12. doi:10.1016/0041-624X(91)90003-Q.

[83] Z. Jiang, J. Ponniah, G. Cascante, R. Haas, Nondestructive ultrasonic testing methodology for condition assessment of hot mix asphalt specimens, 761 (2011) 751–761. doi:10.1139/L11-046.

[84] A. Benter, W. Moore, M. Antolovich, Laboratory measurement of fragmented ore bulk density using ground penetrating radar, Min. Technol. 122 (2013) 250–255. doi:10.1179/1743286313Y.0000000046.

[85] M. Yousuf, T. Morton, Use of Vehicle Noise for Roadways , Bridge , and Infrastructure Health Monitoring, 2014.

[86] H. Bjurström, Non-contact surface wave measurements on pavements, KTH Royal Institute of Technology, 2017.

[87] M. Popik, K. Maser, C. Holzschuher, Using high-speed ground penetrating radar for evaluation of asphalt density measurements, in: Annu. Conf. Exhib. Transp. Assoc. Canada, 2010.

[88] K. Maser, A. Carmichael, Ground Penetrating Radar Evaluation of New Pavement Density, 2015.

[89] S. Kasberg, Ground Penetratin Radar for Density Control, 2017.

[90] Geophysical Survey Systems Inc., PaveScan® RDM, 2017.

[91] Geophysical Survey Systems Inc., PaveScan® RDM Manual, 2017.

[92] BS 594987:2015+A1:2017, Asphalt for roads and other paved areas — Specification for transport , laying , compaction and product type testing protocols, 2017.

[93] BS EN 12697-6:2012, Bituminous mixtures - Test methods for hot mix asphalt - Part 6: Determination of bulk density of bituminous specimens, 2012.

[94] ASTM D2950/D2950M - 14, Standard Test Method for Density of Bituminous Concrete in Place by Nuclear Methods, 2014. doi:10.1520/D2950.

[95] ASTM D7113/D7113M, Standard Test Method for Density of Bituminous Paving Mixtures in Place by the Electromagnetic Surface Contact Methods, 2016. doi:10.1520/D7113.

[96] AASHTO T 343-12, Density of In-Place Hot Mix Asphalt (HMA) Pavement by Electronic Surface Contact Devices, 2016.

[97] E. Kassem, T. Scullion, E. Masad, A. Chowdhury, W. Liu, C. Estakhri, S. Dessouky, Comprehensive Evaluation of Compaction of Asphalt Pavements and Development of Compaction Monitoring System, 2012.

[98] AASHTO PP81-14 (2016), Standard Practice for Intelligent Compaction Technology for Embankment and Asphalt Pavement Applications, 2016.

[99] S. Yoon, M. Hastak, J. Lee, Suitability of Intelligent Compaction for Asphalt Pavement Quality Control and Quality Assurance, J. Constr. Eng. Manag. 144 (2018). doi:10.1061/(ASCE)CO.1943-7862.0001401.

[100] B. Horan, Intelligent Compaction, (2018). http://asphaltmagazine.com/intelligent-compaction/.

[101] D. Dennison, BOMAG AMERICAS - Kewanee, IL, n.d.

[102] Volvo Construction Equipment, Volvo Intelligent Compaction: FAQ, 2015. https://www.volvoce.com/-/media/volvoce/local/americas/northamerica/brochures/products/density-direct/volvo-densitydirect-faq-0315.pdf?v=GzQtPw.

[103] Volvo Construction Equipment, Volvo Intelligent Compaction system with density direct, 2015. doi:https://www.volvoce.com/-/media/volvoce/local/americas/northamerica/brochures/products/density-direct/density-direct-brochure.pdf?v=GzQtPw.

[104] Volvo Construction Equipment, Compact Assist - Intelligent Compaction for Soil and Asphalt Compactors, 2017. doi:https://www.volvoce.com/united-states/en-us/products/other-products/density-direct/.

[105] K. Willoughby, S. Ellis, FHWA Pooled Fund IC Project, 2011.

[106] Caterpillar, CAT® Compaction Control Technologies for Asphalt and Soil, (2016).

[107] F. Akesson, Dynapac Compaction Analyzer and Optimizer, (2018). http://www.intelligentcompaction.com/downloads/Presentation.

[108] S. Rakowski, Intelligent Compaction for Soils and Aspahlt, (2013). http://www.intelligentcompaction.com/downloads/Presentation.

[109] B. Crockett, Introduction of Sakai CIS : “Compaction Information System,” n.d.

[110] FHWA, Intelligent Compaction Technology for Asphalt Applications, 2014.

[111] A. Mohan, S. Poobal, Crack detection using image processing: A critical review and analysis, Alexandria Eng. J. (2017). doi:10.1016/j.aej.2017.01.020.

[112] M. Gavilán, D. Balcones, O. Marcos, D.F. Llorca, M.A. Sotelo, I. Parra, M. Ocaña, P. Aliseda, P. Yarza, A. Amírola, Adaptive road crack detection system by pavement classification, Sensors. 11 (2011) 9628–9657. doi:10.3390/s111009628.

[113] H. Bowden, M.J. Almond, W. Hayes, S. McRobbie, The Use of Diffuse Reflectance Infrared Spectroscopy to Monitor the Oxidation of UV and Naturally Aged Bitumen and Asphalt, (n.d.).

[114] H. Bowden, D. Bateman, S. Mcrobbie, H. Viner, D. Burton, H. England, Alternative techniques in predicting fretting in road surfacing using spectroscopic analysis, in: LJMU, 2018: pp. 1–22.

[115] G. Dondi, M. Barbarella, C. Sangiorgi, C. Lantieri, L. De Marco, A Semi-automatic method for identifying defects on road surfaces, in: Int. Conf. Sustain. Des. Constr., 2011: pp. 704–711.

[116] S. Mcrobbie, C. Wallbank, K. Nesnas, A. Wright, Use of high-resolution 3-D surface data to monitor change over time on pavement surfaces Research into pavement surface disintegration : Phase 3, TRL Ltd, 2015.

[117] G. Furness, S. Barnes, A. Wright, Crack Detection on Local Roads - Phase 2, TRL Ltd, 2007.

[118] Y.J. Tsai, A. Chatterjee, C. Jiang, Challenges and Lessons from the Successful Implementation of Automated Road Condition Surveys on a Large Highway System, in: 25th Eur. Signal Process. Conf. Challenges, 2017: pp. 2085–2089.

[119] S. McRobbie, A. Wright, Crack detection on local roads – Phase 1, TRL Ltd, 2005.

[120] WDM Ltd, RAV – Road Assessment Vehicle Surveys, 2000.

[121] NSW Government, QA Specification R424, 2013.

[122] K.C.P. Wang, W. Gong, Automated pavement distress survey: a review and a new direction, in: Pavement Eval. Conf., 2002: pp. 21–25. http://pms.nevadadot.com/2002presentations/43.Pdf.

[123] T.S. Nguyen, M. Avila, S. Begot, Automatic detection and classification of defect on road pavement using anisotropy measure, in: Eur. Signal Process. Conf., Glasgow, Scotland, 2009: pp. 617–621.

[124] VECTRA France, AMAC® - Multifunction, (2018) 1–6. http://vectrafrance.com.

[125] S. Cafiso, S. Heller, G. Pappalardo, F. Trovato, Visualization tools in support of road asset management, in: Int. Conf. Traffic Transp. Eng., Belgrade, 2016.

[126] Y.-C.J. Tsai, F. Li, Critical Assessment of Detecting Asphalt Pavement Cracks under Different Lighting and Low Intensity Contrast Conditions Using Emerging 3D Laser Technology, J. Transp. Eng. 138 (2012) 649–656. doi:10.1061/(ASCE)TE.1943-5436.0000353.

[127] D. Widyatmoko, Optical Spectroscopy of Binder Condition at Traffic Speed Final Report, 2014.

[128] A. Mei, N. Fiore, R. Salvatori, A. D'Andrea, M. Fontana, Spectroradiometric Laboratory Measures on Asphalt Concrete: Preliminary Results, Procedia - Soc. Behav. Sci. 53 (2012) 514–523. doi:10.1016/j.sbspro.2012.09.902.

[129] Labfacility, Temperature Needle Probe T-shaped - Asphalt or Food Processing 1M /1.4M Type K, (2018) 1–3. https://www.labfacility.com/temperature-type-k-needle-probe-t-shaped-asphalt-or-food-processing.html.

[130] Controls Group, Asphalt digital thermometer, (n.d.). http://www.controls-group.com.

[131] Construction Fasteners & Tools, Milwaukee 2267-20NST, 10:1 Infrared Temp-Gun, Nist calibration, (2018) 1–4. https://cf-t.com/milwaukee-2267-20nst-101-infrared-temp-gun-nist-calibration.

[132] Http://www.fluke.com, Case Study : Ministry of Transport , Quebec, (2018) 2–3. http://www.fluke.com/fluke/sgen/community/fluke-news-plus/articlecategories/ti/lower road maintenance costs.

[133] Land Instruments International, RT8A rugged, high performance infrared thermometer, (2018) 2–3. www.landinst.com.

[134] M.A. Blount, W.E. Baca, H.C. Chui, Principles of Infrared Thermocouples, 1996. doi:10.3778/j.issn.1002-8331.2010.04.052.

[135] BS EN 12697-13:2000, Bituminous mixtures : Test methods for hot mix asphalt - Part 13: Temperature measurement, 2000.

[136] MATtest Southern Ltd, Surveys – Mattest Southern Ltd, (2018) 1–3. http://mattestsouth.co.uk.

[137] MATtest Southern Ltd, C. Freeman, MATtest LSE interview, (2018).

[138] MATtest Southern Ltd, Meeting interview, (2018).

[139] PD ISO/TR 12888, Selected illustrations of gauge repeatability and reproducibility studies, 2011.

[140] B. Pandiripalli, Repeatability and Reproducibility Studies: a Comparison of Techniques, 2007. doi:10.1017/CBO9781107415324.004.

[141] L. Khazanovich, K. Hoegh, M. Turos, D. Tompkins, R. Conway, Testing Protocol for the Rolling Density Meter, 2016.

[142] Geophysical Survey Systems Inc., New Radio Wave Technology Assesses Asphalt Integrity, 2018.

[143] A. Michael, Asphalt Compaction Assessment with Small Form-Factor GPR Antennas Providing Real-Time Dielectric Measurements, (2018). https://www.linkedin.com/pulse/asphalt-compaction-assessment-small-form-factor-gpr-michael-arvanitis/.

[144] L. Khazanovich, R. Conway, RDM Survey Report: Nebraska SHRP2 Product R06C Implementation Activities, 2016.

[145] L. Khazanovich, R. Conway, RDM Survey Report: Maine SHRP2 Product R06C Implementation Activities, 2016.

[146] MATtest Southern Ltd, BIM and Data Capture During Road Construction, 2018.

Appendix A – LSE v. RSE comparative study

The total number of irregularities above 4 mm, 7 mm and 10 mm detected by LSE and RSE systems for the schemes surveyed are reported from Table 14 to Table 25.

Table 14: LSE *v.* RSE – M1 J5

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M1 J5, SB, L1, Ch. 0-97 NS	2	2	0	0	0	0
M1 J5, SB, L1, Ch. 0-97 OS	1	2	0	0	0	0
M1 J5, SB, L2, Ch. 0-95 NS	2	1	0	0	0	0
M1 J5, SB, L2, Ch. 0-95 OS	3	2	0	0	0	0
M1 J5, SB, L3, Ch. 0-95 NS	1	3	1	0	0	0
M1 J5, SB, L3, Ch. 0-95 OS	0	0	1	2	0	0

Table 15: LSE *v.* RSE – M25 J25

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M25 J25, WB, L1, Ch. 0-87 NS	2	1	0	0	0	0
M25 J25, WB, L1, Ch. 0-87 OS	1	1	0	0	0	0
M25 J25, WB, L2, Ch. 0-89 NS	2	2	0	0	0	0
M25 J25, WB, L2, Ch. 0-89 OS	3	1	0	0	0	0

Table 16: LSE *v.* RSE – M25 J28

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M25 J28, SB, L1, Ch. 0-164 NS	5	5	0	0	0	0
M25 J28, SB, L1, Ch. 0-164 OS	5	3	0	0	0	0
M25 J28, SB, L2, Ch. 0-167 NS	5	4	1	1	0	0
M25 J28, SB, L2, Ch. 0-167 OS	3	4	0	1	0	0

Table 17: LSE *v.* RSE – M25 J23

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M25 J23, RB (North), L1, Ch. 0-89 NS	2	3	0	0	0	0
M25 J23, RB (North), L1, Ch. 0-89 OS	2	2	0	0	0	0
M25 J23, RB (North), L2, Ch. 0-89 NS	2	2	0	0	0	0
M25 J23, RB (South), L1, Ch. 0-96 OS	3	3	0	0	0	0
M25 J23, RB (South), L2, Ch. 0-97 OS2	2	2	1	0	0	0

Table 18: LSE *v.* RSE – M4 J4

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M4 J4, EB, L1, Ch. 0-122 NS	0	1	0	0	0	0
M4 J4, EB, L1, Ch. 0-122 OS	2	1	0	0	0	0
M4 J4, EB, L2, Ch. 0-118 NS	0	1	0	0	0	0
M4 J4, EB, L2, Ch. 0-118 OS	1	2	0	0	0	0

Table 19: LSE *v.* RSE – M4 J4 Heathrow Spur Road

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M4 J4 Heathrow Spur Road, NB, L1, Ch. 0-300	1	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L1, Ch. 300-600	3	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L1, Ch. 600-900	0	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L1, Ch. 900-1200	2	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L1, Ch. 1200-1257	1	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L2, Ch. 0-300	0	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L2, Ch. 300-600	1	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L2, Ch. 600-900	0	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L2, Ch. 900-1196	2	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L3, Ch. 0-300	2	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L3, Ch. 300-600	2	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L3, Ch. 600-900	1	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L3, Ch. 900-1189	1	0	0	0	0	0
M4 J4 Heathrow Spur Road, NB, L1 Onslip, Ch. 0-160	0	0	0	0	0	0

Table 20: LSE *v.* RSE – A76 North of Garleffan

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
A76 North of Garleffan, RB (NB), L1, Ch. 0-300	5	5	0	0	0	0
A76 North of Garleffan, RB (SB), L1, Ch. 0-300	5	3	2	0	0	2

Table 21: LSE *v.* RSE – A82 Garshake Road

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
A82 Garshake Road, SB, L1, Ch. 0-300 NS	8	3	0	0	0	0
A82 Garshake Road, SB, L1, Ch. 300-600 NS	3	1	1	0	0	0
A82 Garshake Road, SB, L1, Ch. 600-900 NS	2	2	0	0	0	0
A82 Garshake Road, SB, L2, Ch. 0-300 OS	5	1	0	0	0	0
A82 Garshake Road, SB, L2, Ch. 300-600 OS	0	0	0	0	0	0
A82 Garshake Road, SB, L2, Ch. 600-900 OS	1	1	0	1	0	0

Table 22: LSE *v.* RSE – M8 Arkleston

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M8 Arkleston, WB, L1, Ch. 0-300	3	3	0	0	0	0
M8 Arkleston, WB, L1, Ch. 300-600	3	4	0	0	0	0
M8 Arkleston, WB, L1, Ch. 600-675	0	0	0	0	0	0
M8 Arkleston, WB, L1, Ch. 630-705 (Overlap)	1	0	0	0	0	0
M8 Arkleston, WB, L2, Ch. 135-435	0	0	0	0	0	0
M8 Arkleston, WB, L2, Ch. 435-510	2	1	0	0	0	0
M8 Arkleston, WB, L2, Ch. 510-585	0	0	0	0	0	0
M8 Arkleston, WB, L2, Ch. 585-660	0	0	0	0	0	0
M8 Arkleston, WB, L2, Ch. 630-705 (Overlap)	1	0	0	1	0	0

Table 23: LSE *v.* RSE – M1 J16-J19

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M1 J16-J19, NB, L1, (1)	0	2	0	0	0	0
M1 J16-J19, NB, L1, (2)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (3)	1	1	0	0	0	0
M1 J16-J19, NB, L1, (4)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (5)	0	1	0	0	0	0
M1 J16-J19, NB, L1, (6)	0	3	0	0	0	0
M1 J16-J19, NB, L1, (7)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (8)	0	2	0	0	0	0
M1 J16-J19, NB, L1, (9)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (10)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (11)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (12)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (13)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (14)	0	1	0	0	0	0
M1 J16-J19, NB, L1, (15)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (16)	1	0	0	0	0	0

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
M1 J16-J19, NB, L1, (17)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (18)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (19)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (20)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (21)	1	1	0	0	0	0
M1 J16-J19, NB, L1, (22)	0	1	0	0	0	0
M1 J16-J19, NB, L1, (23)	2	1	0	0	0	0
M1 J16-J19, NB, L1, (24)	0	1	0	0	0	0
M1 J16-J19, NB, L1, (25)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (26)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (27)	0	0	0	0	0	0
M1 J16-J19, NB, L1, (28)	1	1	0	0	0	0
M1 J16-J19, SB, L1, (1)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (2)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (3)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (4)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (5)	0	1	0	0	0	0
M1 J16-J19, SB, L1, (6)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (7)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (8)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (9)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (10)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (11)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (12)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (13)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (14)	1	1	0	0	0	0
M1 J16-J19, SB, L1, (15)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (16)	2	2	0	0	0	0
M1 J16-J19, SB, L1, (17)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (18)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (19)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (20)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (21)	0	0	0	0	0	0
M1 J16-J19, SB, L1, (22)	1	1	0	0	0	0
M1 J16-J19, SB, L1, (23)	1	0	0	0	0	0

Table 24: LSE *v.* RSE – A269 Ninfield Road

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
A269 Ninfield Road, EB, L1, Ch. 0-300	4	2	3	0	2	0
A269 Ninfield Road, EB, L1, Ch. 300-375	2	0	1	0	0	0
A269 Ninfield Road, WB, L1, Ch. 375-75	7	0	0	0	0	0
A269 Ninfield Road, WB, L1, Ch. 75-0	1	1	3	0	0	0
A269 Ninfield Road, EB, L1, Ch. 375-675	2	3	1	0	0	0
A269 Ninfield Road, EB, L1, Ch. 675-700	0	0	1	1	0	0
A269 Ninfield Road, WB, L1, Ch. 700-400	6	2	1	0	3	0
A269 Ninfield Road, WB, L1, Ch. 400-375	0	1	0	0	0	0
A269 Ninfield Road, NB, L1, Ch. 0-285	13	5	2	0	0	0
A269 Ninfield Road, SB, L1, Ch. 0-285	8	8	1	0	1	0

Table 25: LSE *v.* RSE – A46 Hobby Horse to Widmerpool

Name ID	No. of Surface irregularities above 4 mm		No. of Surface irregularities above 7 mm		No. of Surface irregularities above 10 mm	
	LSE	RSE	LSE	RSE	LSE	RSE
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 550-760	1	0	0	0	0	0
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 1165-1305	1	1	0	0	0	0
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 1305-1605	2	1	1	0	0	0
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 1605-1905	0	1	0	0	0	0
A46 Hobby Horse to Widmerpool, SB, L1, Ch. 17662-17855	5	0	1	0	0	0
A46 Hobby Horse to Widmerpool, SB, Slip Road, Ch. 0-259	2	0	2	0	0	0

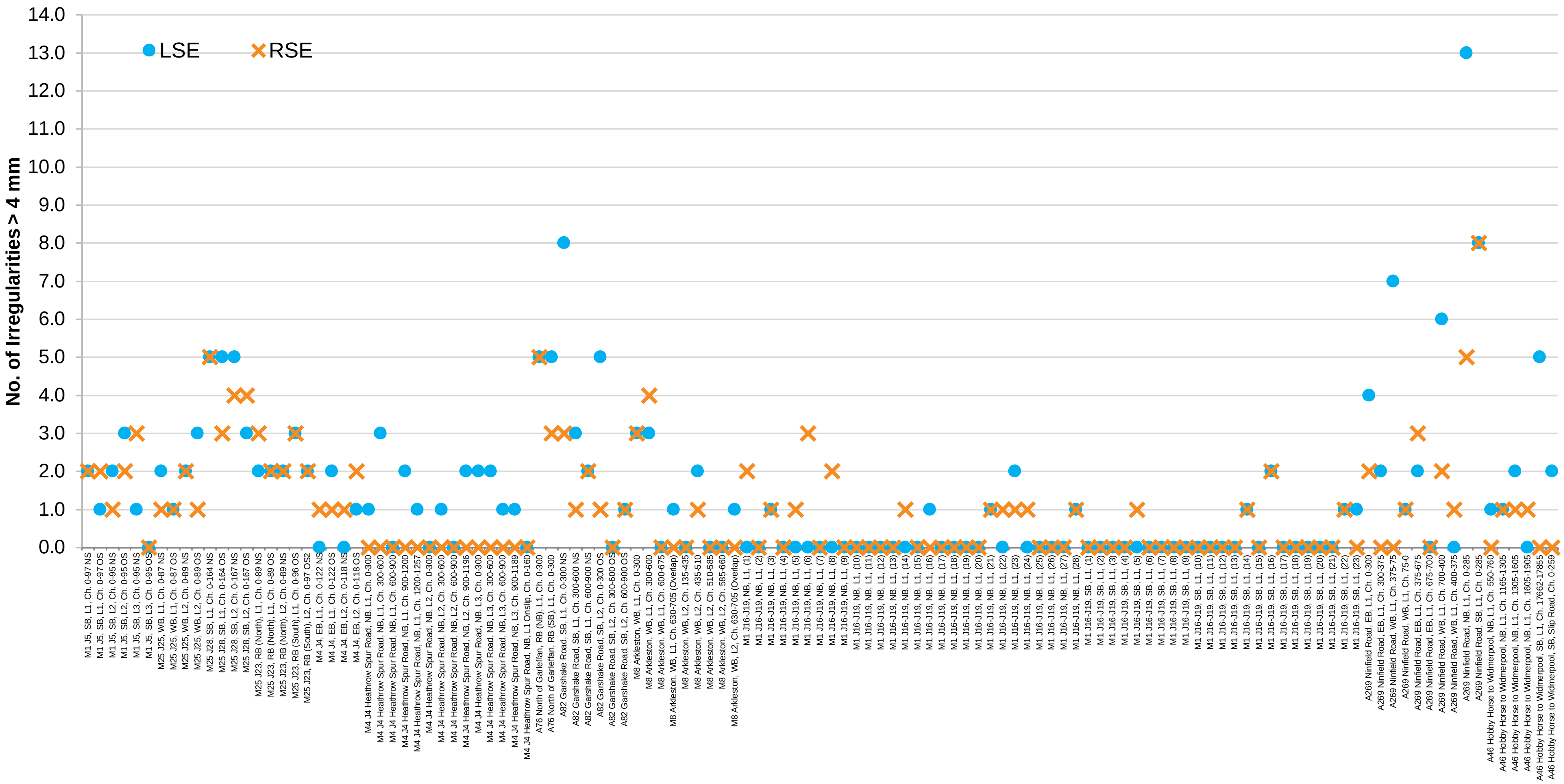


Figure 23 – LSE vs RSE number of surface irregularities above 4 mm

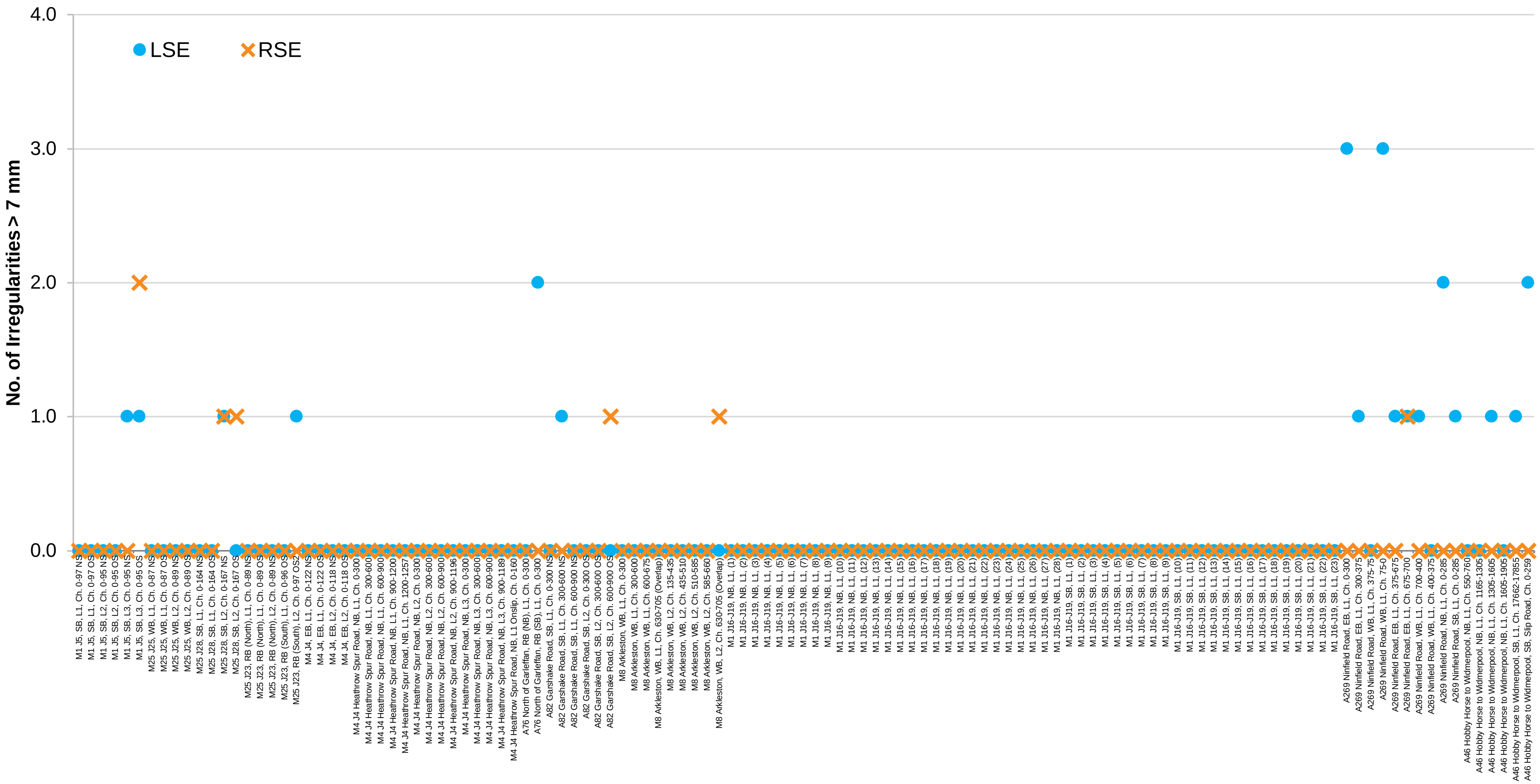


Figure 24 – LSE vs RSE number of surface irregularities above 7 mm

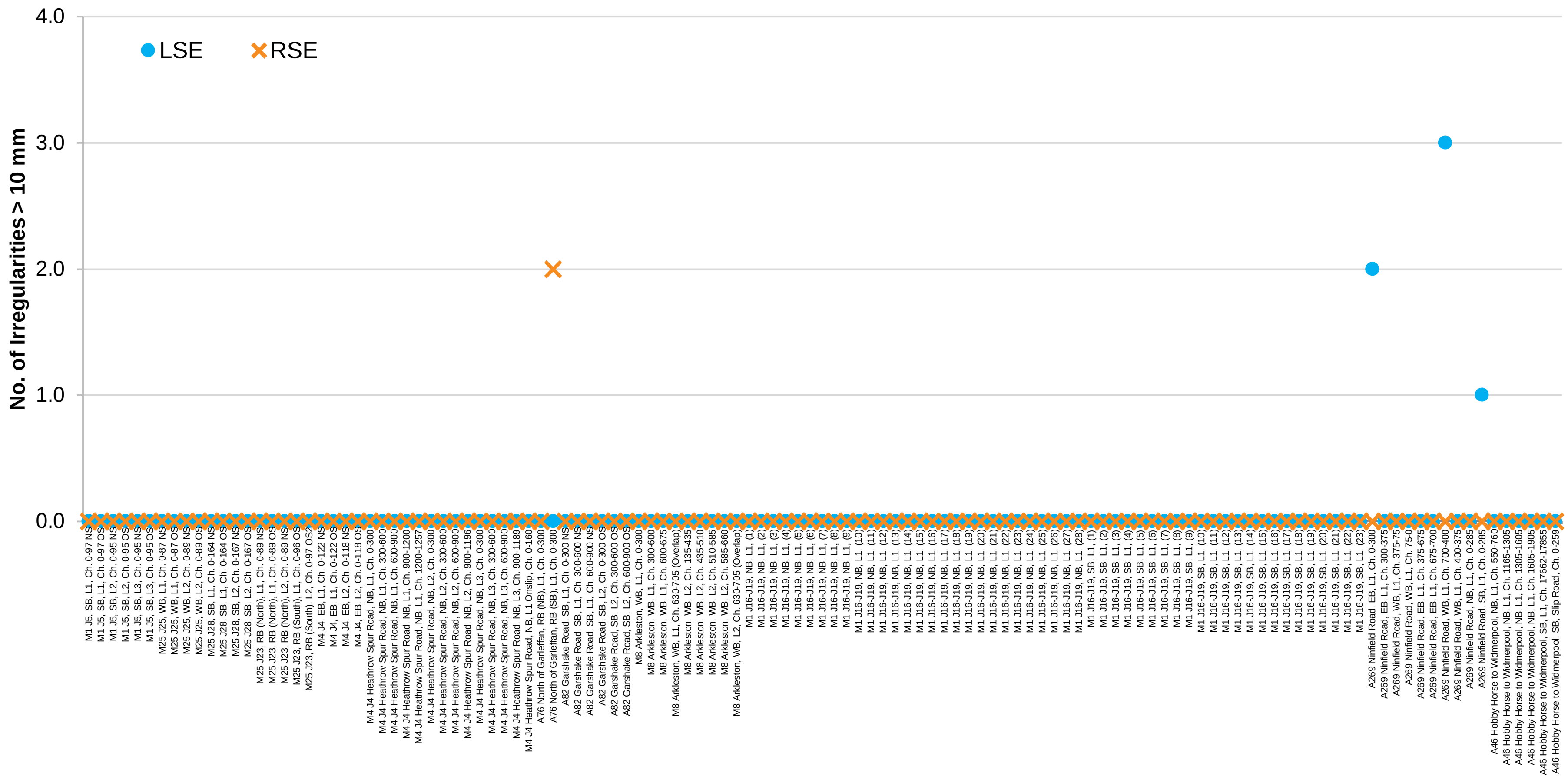


Figure 25 – LSE vs RSE number of surface irregularities above 10 mm

Appendix B – 3D-TD v. Volumetric Patch comparative study

The average texture depth measured by 3D-TD system and Volumetric Patch for the schemes surveyed are reported from Table 26 to Table 37.

Table 26: 3D-TD vs Volumetric Patch – M1 J5

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
M1 J5, SB, L1, Ch. 0-50 NS1	10	0.53	0.46	14%
M1 J5, SB, L1, Ch. 0-50 NS2	10	0.49	0.48	3%
M1 J5, SB, L1, Ch. 0-50 OS1	10	0.49	0.48	3%
M1 J5, SB, L1, Ch. 0-50 OS2	10	0.47	0.48	-2%
M1 J5, SB, L2, Ch. 0-50 NS1	10	0.52	0.56	-7%
M1 J5, SB, L2, Ch. 0-50 NS2	10	0.58	0.55	6%
M1 J5, SB, L2, Ch. 0-50 OS1	10	0.54	0.55	-2%
M1 J5, SB, L2, Ch. 0-50 OS2	10	0.56	0.58	-4%
M1 J5, SB, L3, Ch. 0-50 NS1	10	0.54	0.54	1%
M1 J5, SB, L3, Ch. 0-50 NS2	10	0.61	0.51	21%
M1 J5, SB, L3, Ch. 0-50 OS1	10	0.52	0.54	-4%
M1 J5, SB, L3, Ch. 0-50 OS2	10	0.59	0.54	10%

Table 27: 3D-TD vs Volumetric Patch – M25 J25

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
M25 J25, WB, L1, Ch. 5-55 NS1	10	0.47	0.46	1%
M25 J25, WB, L1, Ch. 5-55 NS2	10	0.45	0.47	-4%
M25 J25, WB, L1, Ch. 5-55 OS1	10	0.44	0.55	-19%
M25 J25, WB, L1, Ch. 5-55 OS2	10	0.41	0.45	-8%
M25 J25, WB, L2, Ch. 5-55 NS1	10	0.46	0.47	-3%
M25 J25, WB, L2, Ch. 5-55 NS2	10	0.44	0.49	-9%
M25 J25, WB, L2, Ch. 5-55 OS1	10	0.45	0.41	10%
M25 J25, WB, L2, Ch. 5-55 OS2	10	0.48	0.48	0%

Table 28: 3D-TD vs Volumetric Patch – M25 J28

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
M25 J28, SB, L1, Ch. 0-50 NS1	10	0.7	0.8	-13%
M25 J28, SB, L1, Ch. 0-50 NS2	10	0.6	0.7	-14%
M25 J28, SB, L1, Ch. 0-50 OS1	10	0.7	0.8	-13%
M25 J28, SB, L1, Ch. 0-50 OS2	10	0.7	0.7	0%
M25 J28, SB, L2, Ch. 0-50 NS1	10	0.7	0.8	-13%
M25 J28, SB, L2, Ch. 0-50 NS2	10	0.6	0.7	-14%
M25 J28, SB, L2, Ch. 0-50 OS1	10	0.7	0.8	-13%
M25 J28, SB, L2, Ch. 0-50 OS2	10	0.6	0.7	-14%
M25 J28, SB, L1, Ch. 60-110 NS1	10	0.7	0.7	0%
M25 J28, SB, L1, Ch. 60-110 NS2	10	0.8	0.7	14%
M25 J28, SB, L1, Ch. 60-110 OS1	10	0.8	0.9	-11%
M25 J28, SB, L1, Ch. 60-110 OS2	10	0.7	0.7	0%
M25 J28, SB, L2, Ch. 60-110 NS1	10	0.7	0.8	-13%
M25 J28, SB, L2, Ch. 60-110 NS2	10	0.7	0.6	17%
M25 J28, SB, L2, Ch. 60-110 OS1	10	0.7	0.8	-13%
M25 J28, SB, L2, Ch. 60-110 OS2	10	0.6	0.5	20%

Table 29: 3D-TD vs Volumetric Patch – M25 J23

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
M25 J23, RB (North), L1, Ch. 0-50 NS1	10	0.6	0.6	0%
M25 J23, RB (North), L1, Ch. 0-50 NS2	10	0.6	0.5	20%
M25 J23, RB (North), L1, Ch. 0-50 OS1	10	0.6	0.6	0%
M25 J23, RB (North), L1, Ch. 0-50 OS2	10	0.6	0.5	20%
M25 J23, RB (North), L2, Ch. 0-50 NS1	10	0.6	0.6	0%
M25 J23, RB (North), L2, Ch. 0-50 OS1	10	0.5	0.5	0%
M25 J23, RB (North), L3, Ch. 0-50 NS1	10	0.7	0.7	0%
M25 J23, RB (North), L3, Ch. 0-50 NS2	10	0.7	0.6	17%
M25 J23, RB (North), L3, Ch. 0-50 OS1	10	0.6	0.6	0%
M25 J23, RB (South), L1, Ch. 0-50 NS1	10	0.5	0.5	0%
M25 J23, RB (South), L1, Ch. 0-50 NS2	10	0.5	0.5	0%
M25 J23, RB (South), L1, Ch. 0-50 OS1	10	0.5	0.5	0%
M25 J23, RB (South), L1, Ch. 0-50 OS2	10	0.5	0.5	0%
M25 J23, RB (South), L2, Ch. 0-50 NS1	10	0.5	0.5	0%
M25 J23, RB (South), L2, Ch. 0-50 OS1	10	0.5	0.5	0%
M25 J23, RB (South), L2, Ch. 0-50 OS2	10	0.5	0.5	0%
M25 J23, RB (South), L3, Ch. 0-50 NS1	10	0.6	0.5	20%

Table 30: 3D-TD vs Volumetric Patch – M4 J4

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
M4 J4, EB, L1, Ch. 0-50 NS1	10	0.6	0.6	0%
M4 J4, EB, L1, Ch. 0-50 NS2	10	0.6	0.6	0%
M4 J4, EB, L1, Ch. 0-50 OS1	10	0.5	0.6	-17%
M4 J4, EB, L1, Ch. 0-50 OS2	10	0.5	0.6	-17%
M4 J4, EB, L2, Ch. 0-50 NS1	10	0.6	0.7	-14%
M4 J4, EB, L2, Ch. 0-50 NS2	10	0.7	0.7	0%
M4 J4, EB, L2, Ch. 0-50 OS1	10	0.6	0.7	-14%
M4 J4, EB, L2, Ch. 0-50 OS2	10	0.6	0.7	-14%

Table 31: 3D-TD vs Volumetric Patch – M4 J4 Heathrow Spur Road

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
M4 J4 Heathrow Spur Road, NB, L1, Ch. 600-650	10	1.44	1.4	3%
M4 J4 Heathrow Spur Road, NB, L1, Ch. 850-900	10	1.52	1.4	9%
M4 J4 Heathrow Spur Road, NB, L2, Ch. 175-225	10	1.35	1.3	4%
M4 J4 Heathrow Spur Road, NB, L2, Ch. 425-475	10	1.53	1.4	9%
M4 J4 Heathrow Spur Road, NB, L2, Ch. 675-725	10	1.55	1.4	11%
M4 J4 Heathrow Spur Road, NB, L3, Ch. 600-650	10	1.56	1.4	12%
M4 J4 Heathrow Spur Road, NB, L3, Ch. 850-900	10	1.50	1.4	7%

Table 32: 3D-TD vs Volumetric Patch – A76 North of Garleffan

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
A76 North of Garleffan, RB (NB), L1, Ch. 0-50	10	0.86	0.8	7%
A76 North of Garleffan, RB (SB), L1, Ch. 0-50	10	0.8	0.7	14%

Table 33: 3D-TD vs Volumetric Patch – A82 Garshake Road

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
A82 Garshake Road, SB, L1, Ch. 100-150 NS	10	0.82	0.8	2%
A82 Garshake Road, SB, L1, Ch. 100-150 Centreline	10	0.89	0.91	-2%
A82 Garshake Road, SB, L2, Ch. 100-150 NS	10	0.96	0.84	14%
A82 Garshake Road, SB, L2, Ch. 100-150 Centreline	10	0.87	0.78	12%
A82 Garshake Road, SB, L2, Ch. 450-500 NS	10	0.92	0.9	2%
A82 Garshake Road, SB, L2, Ch. 450-500 Centreline	10	0.85	0.78	9%
A82 Garshake Road, SB, L2, Ch. 700-750 NS	10	0.88	0.75	17%
A82 Garshake Road, SB, L2, Ch. 700-750 Centreline	10	0.87	0.67	30%

Table 34: 3D-TD vs Volumetric Patch – M8 Arkleston

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
M8 J27 Arkleston, WB, L1, Ch. 100-150	10	0.93	1	-7%
M8 J27 Arkleston, WB, L1, Ch. 600-650	10	0.98	0.9	9%
M8 J27 Arkleston, WB, L2, Ch. 200-250	10	0.87	0.9	-3%
M8 J27 Arkleston, WB, L3, Ch. 100-150	10	0.97	1	-3%
M8 J27 Arkleston, WB, L3, Ch. 400-450	10	0.92	0.9	2%
M8 J29-J28 Arkleston, EB, Onslip, Ch. 220-270	10	0.8	1	-20%

Table 35: 3D-TD vs Volumetric Patch – M1 J16-J19

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
M1 J16-J19, NB, L1, (1)	14	1.38	1.3	6%
M1 J16-J19, NB, L1, (2)	14	1.2	1.3	-8%
M1 J16-J19, NB, L1, (3)	14	1.35	1.4	-4%
M1 J16-J19, NB, L1, (4)	14	1.12	1.3	-14%
M1 J16-J19, NB, L1, (5)	14	1.16	1.3	-11%
M1 J16-J19, NB, L1, (6)	14	1.36	1.4	-3%
M1 J16-J19, NB, L1, (7)	14	1.29	1.3	-1%
M1 J16-J19, NB, L1, (8)	14	1.15	1.4	-18%
M1 J16-J19, NB, L1, (9)	14	1.25	1.3	-4%
M1 J16-J19, NB, L1, (10)	14	1.21	1.4	-14%
M1 J16-J19, NB, L1, (11)	14	1.21	1.4	-14%
M1 J16-J19, NB, L1, (12)	14	1.28	1.4	-9%
M1 J16-J19, NB, L1, (13)	14	1.33	1.4	-5%
M1 J16-J19, NB, L1, (14)	14	1.41	1.4	1%
M1 J16-J19, NB, L1, (15)	14	1.36	1.4	-3%
M1 J16-J19, NB, L1, (16)	14	1.29	1.4	-8%
M1 J16-J19, NB, L1, (17)	14	1.34	1.4	-4%
M1 J16-J19, NB, L1, (18)	14	1.3	1.3	0%
M1 J16-J19, NB, L1, (19)	14	1.23	1.3	-5%
M1 J16-J19, NB, L1, (20)	14	1.21	1.3	-7%
M1 J16-J19, NB, L1, (21)	14	1.19	1.3	-8%
M1 J16-J19, NB, L1, (22)	14	1.4	1.4	0%
M1 J16-J19, NB, L1, (23)	14	1.27	1.4	-9%
M1 J16-J19, NB, L1, (24)	14	1.4	1.4	0%
M1 J16-J19, NB, L1, (25)	14	1.41	1.5	-6%
M1 J16-J19, SB, L1, (1)	14	1.22	1.3	-6%
M1 J16-J19, SB, L1, (2)	14	1.42	1.3	9%
M1 J16-J19, SB, L1, (3)	14	1.31	1.3	1%
M1 J16-J19, SB, L1, (4)	14	1.28	1.3	-2%
M1 J16-J19, SB, L1, (5)	14	1.2	1.3	-8%
M1 J16-J19, SB, L1, (6)	14	1.29	1.4	-8%
M1 J16-J19, SB, L1, (7)	14	1.2	1.4	-14%
M1 J16-J19, SB, L1, (8)	14	1.35	1.3	4%
M1 J16-J19, SB, L1, (9)	14	1.3	1.3	0%
M1 J16-J19, SB, L1, (10)	14	1.39	1.4	-1%
M1 J16-J19, SB, L1, (11)	14	1.39	1.3	7%
M1 J16-J19, SB, L1, (12)	14	1.48	1.4	6%
M1 J16-J19, SB, L1, (13)	14	1.37	1.3	5%
M1 J16-J19, SB, L1, (14)	14	1.4	1.3	8%
M1 J16-J19, SB, L1, (15)	14	1.42	1.4	1%

Table 36: 3D-TD vs Volumetric Patch – A269 Ninfield Road

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
A269 Ninfield Road, EB, L1, Ch. 180-230	10	1.35	1.3	4%
A269 Ninfield Road, WB, L1, Ch. 230-180	10	1.42	1.3	9%
A269 Ninfield Road, EB, L1, Ch. 380-430	10	1.39	1.3	7%
A269 Ninfield Road, WB, L1, Ch. 430-380	10	1.38	1.3	6%
A269 Ninfield Road, NB, L1, Ch. 110-155	10	1.4	1.3	8%
A269 Ninfield Road, SB, L1, Ch. 110-155	10	1.4	1.3	8%

Table 37: 3D-TD vs Volumetric Patch – A46 Hobby Horse to Widmerpool

Name ID	Aggregate Nominal Size (mm)	Average Mean Texture Depth (mm)		Measurement difference (%)
		3D-TD [a]	Volumetric Patch [b]	[c] = ([a]-[b])/[b]
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 0-50	14	1.11	1	11%
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 200-250	14	1.02	1.2	-15%
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 500-550	14	0.98	1.2	-18%
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 1200-1250	14	1.04	1.1	-5%
A46 Hobby Horse to Widmerpool, NB, L1, Ch. 1500-1550	14	1.02	1.3	-22%
A46 Hobby Horse to Widmerpool, SB, L1 (Slip Road), Ch. 0-50	14	1.19	1.3	-8%
A46 Hobby Horse to Widmerpool, RB, L4, Ch. 53-103	10	1.59	1.6	-1%
A46 Hobby Horse to Widmerpool, RB, L3, Ch. 53-103	10	1.5	1.4	7%
A46 Hobby Horse to Widmerpool, RB, L2, Ch. 53-103	10	1.5	1.5	0%
A46 Hobby Horse to Widmerpool, RB, L1, Ch. 53-103	10	1.43	1.5	-5%

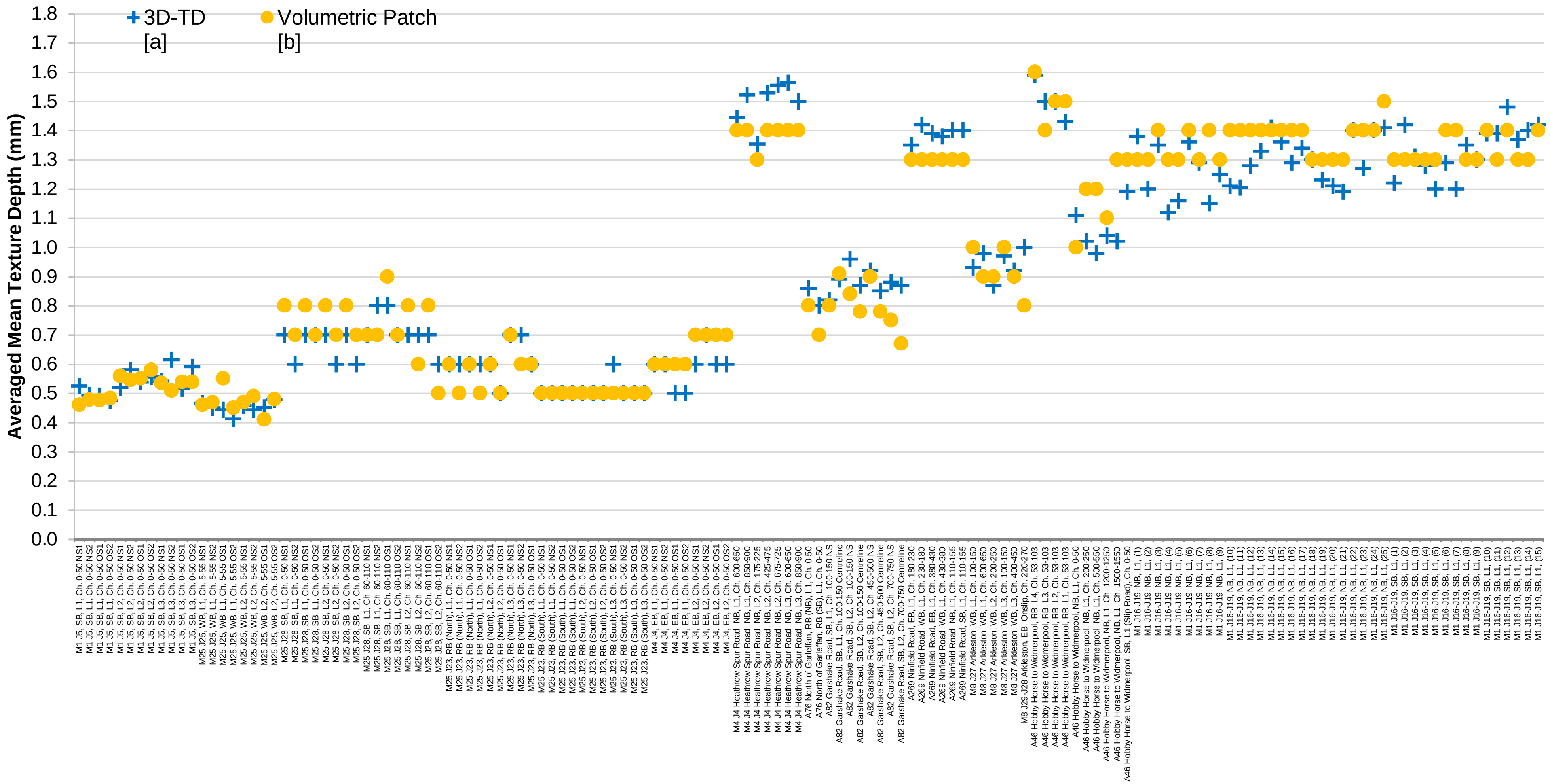


Figure 26 –3D-TD vs Volumetric Patch measurements per each location

aecom.com