VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF ROADS

Ignas Kaveckas

CONCEPT OF AUTOMATED REGISTRATION OF QUALITY PARAMETERS OF ASPHALT LAYER INSTALLATION

ASFALTO SLUOKSNIŲ ĮRENGIMO KOKYBINIŲ PARAMETRŲ AUTOMATIZUOTO REGISTRAVIMO KONCEPCIJA

Master‘s degree Thesis

Innovative Road and Bridge Engineering study programme, state code 6281EX002
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Supervisor prof. dr. Audrius Vaitkus
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OBJECTIVES FOR MASTER THESIS

No. IKTfmu-22-5590

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For student Ignas Kaveckas

Master Thesis title: Concept of Automated Registration of Quality Parameters of Asphalt Layer Installation

Deadline for completion of the final work according to the planned study schedule.

THE OBJECTIVES:

Explanatory note:
This master`s thesis is devoted to examining the possibilities of determining the properties of asphalt layers using automated methods. An analysis of the experience of other countries in the application of automated methods to determine the properties of constructed asphalt layers will be carried out. During the experimental study, the properties of the constructed asphalt layers determined by standard and automated methods will be evaluated. The result of the master`s thesis is conclusions based on experimental research and suggestions for the application of automated methods in performing the qualitative parameters of the installation of asphalt layers.
Objective is to develope methodology for asphalt layers installation quality evaluation by means of automated registration of parametrs.
Mayor elements: intelligent production, intelligent transportation and loading, intelligent paving, inteligent compaction, ilteligent measuring

Academic Supervisor Professor Audrius Vaitkus

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Antrosios pakopos studijų **Inovatyvios kelių ir tiltų inžinerijos** programos magistro baigiamasis darbas 3 (keliai ir tiltai)	
Pavadinimas	**Asfalto sluoksnių įrengimo kokybinių parametrų automatizuoto registravimo koncepcija**
Autorius	**Ignas Kaveckas**
Vadovas	**Audrius Vaitkus**

Kalba: anglų

Anotacija

Šiai laikais visi naujai pakloti asfalto sluoksniai yra vertinami ir kontroliuojami įprastiniu ardančiuoju būdu, kuris nesuteikia duomenų ir rezultatų realiu laiku nei kelių tiesybos rangovui nei užsakovui. Šio baigiamojo darbo tikslas – įvertinti asfalto sluoksnio įrengimo kokybės parametrų automatizuoto registravimo metodikas ir jų panaudojimo galimybes. Tyrėjai pažymi, kad tankinimo ir temperatūros registravimo įrenginiai ir sistemos šiuo metu yra labiausiai pažengusios, bet vis dar testavimo stadijose dėl duomenų panaudojimo patikimumo ir paskirties. Šiaurės Europos šalys pristatė premijų sistemos metodiką, skatinančią rangovus naudotis automatizuotomis registravimo sistemomis bei didinti atliekamų darbų kokybę. Buvo atliktas eksperimentinis pakloto asfalto sutankinimo/atsparos tyrimas, kuriuo gauti duomenys rodo ribotą automatizuotų metodų patikimumą lyginant su ardančiųjų bandymų rezultatais. Specialistų apklausa parodė, kad 3 iš 8 rangovų kasdieniuose statybos darbuose naudoja automatizuoto registravimo technologijas, kurios fiksuoja tankinimo volų pravažiavimų skaičių, tankinamo sluoksnio temperatūrą bei atsparumo modulį. Ženkliai didesnį rangovų įsitraukimą laiduotų premijų sistemos įdiegimas arba mažesni šių technologijų kaštai, teigia specialistai. Respondentų nuomone, automatizuotos registracijos technologijos žymiai padidintų kelių tiesimo kokybę, tačiau šiuo metu jos yra per brangios naudoti be papildomo skatinimo. Technikos operatorių kompetencijos stoka ir neparengta teisinė bazė yra pagrindiniai trūkumai. Magistro baigiamasis darbas susideda iš 82 puslapių, kuriame yra 43 paveikslai, 13 lentelių ir 59 literatūros šaltiniai.

Prasminiai žodžiai: Asfalto sluoksnis, asfalto danga, asfalto klojimas, sutankinimas, tankis, oro tuštymės, temperatūra, automatizuotas registravimas, kokybiniai parametrai.

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Annotation

Nowadays all newly paved asphalt layers are assessed and controlled by conventional destructive methodology, which does not provide data and results on real-time for contractors and customers. The purpose of this thesis is to evaluate the methodologies used for the automated registration of quality parameters of asphalt layer installation and the possibilities for their usage. Researchers note that compaction and temperature registration devices and systems are currently the most advanced, but are still in the testing phases for reliability and purpose of using the data. The Northern European countries introduced the bonus system methodology, which encourages contractors to use automated registration systems and to increase the quality of the road construction work performed. An experimental study of asphalt pavement compaction/resistance was conducted, and the data obtained show the limited reliability of automated methods compared to the results of destructive tests. A survey of specialists showed that 3 out of 8 contractors use automated registration technologies in their daily construction work, which record the number of compaction roller passes, the temperature of the compacted layer, and the modulus of resistance. The implementation of a bonus system or lower costs of these technologies would ensure a significantly higher involvement of contractors, specialists say. According to respondents, automated registration technologies would significantly improve the quality of road construction but are currently too expensive to use without additional incentives. The lack of competence of technical operators of mechanisms and an unprepared legal basis framework are the main disadvantages. Master's thesis consists of 82 pages that include 43 figures, 13 tables, and 59 references.

Keywords: Asphalt layer, asphalt pavement, asphalt paving, compaction, density, air voids, temperature, automated registration, quality parameters.

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DECLARATION OF AUTHORSHIP IN FINAL DEGREE THESIS

2023 December 27

(Date)

I confirm that my final degree thesis, which topic is Concept of automated registration of quality parameters of asphalt layer installation

is written independently. The material presented in this final degree thesis is not plagiarized. Quotations from other sources used directly or indirectly are indicated in the literature references.

During the selection and evaluation of the material and the preparation of the thesis, I was advised by scientists and specialists: -

My supervisor is prof. dr. Audrius Vaitkus

There is no contribution of other persons to the final degree thesis. I have not paid any statutory sums of money for this work.

IGNAS KAVECKAS

Signature (Name and Surname)

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LIST OF ABBREVIATIONS

AC – Asphalt concrete

ATU – Automated temperature unit

GPR - Ground Penetrating Radar

GPS - Global Positioning System

HMA - Hot mixture asphalt

IC – Intelligent Compaction

ICMV – Intelligent Compaction measurement values

IR – Infrared

IRI - International roughness index

MA - Mastic asphalt

MTV - Material Transfer Vehicles

NDG - Nuclear density gauge

NDT – Non-destructuve technologies

PA – Porous asphalt

PQI – Pavement Quality Indicator

QA - Quality assurance

QC - Quality control

SMA – Stone-mastic asphalt

INTRODUCTION

Relevance of the topic – Low quality of asphalt roads installation in recent years in Lithuania led to a discussions about new technologies to register automatically all the quality parameters of the asphalt pavement layer on site on real-time and in the whole road section. This could lead to better quality of asphalt roads, faster and probably more accurate laboratory examinations of the installed asphalt layer.

Problem – Nowadays the quality of the installation of asphalt pavement layer is evaluated only by old methods, such as extraction of the cores from the road section and comparison with the cores made in the laboratory. This method harms the pavement layer surface quality, comfort for drivers, and the examination is foreseen at one point.

Research object - The automated monitoring process of the quality parameters of the asphalt layer.

Aim - The objective is to understand the methodologies used for the quality evaluation of asphalt layer installation by automated registration of the parameters and the possibilities for the usage in the future.

Tasks:

1. To review literature on asphalt layer installation process.
2. To review literature on asphalt layers (base, binder, wearing) installation quality requirements.
3. To review literature on automated registration of quality parameters of asphalt layer installation.
4. To select and describe experimental research subject and methodology.
5. To perform experimental research on site when automated asphalt layer installation is performed and to analyse the received data.
6. To perform a survey of specialists regarding automated asphalt layer installation and analyse the received data.
7. To provide conclusions and recommendations regarding automated registration of quality parameters of asphalt layer installation.

Research Methods - An analysis of the literature of the experience of other countries in the application of automated methods to determine the properties of constructed asphalt layers will be carried out. In addition, a literature analysis will be performed on asphalt layer quality parameters and their influence on pavement construction design life. The experimental study will be used to determine the properties of the constructed asphalt layers by standard and automated methods. Survey of specialists will be conducted in order to understand general opinions.

Hypothesis:

- The registration of various parameters of the installation of the asphalt layer installation parameters (eg. temperature in the truck, paver, layer, change in layer compaction (dynamic response), layer width, cross-sectional slope) led to the acquisition of comparative data with the technical specification methods.
- Construction process and quality can be significantly improved by using automated asphalt layer installation parameters registration on site.

Practical significance of work results – Regarding the experimental part of this work, where the automated registration of asphalt layer quality parameters will be compared with technical specifications methods, the construction companies could know the difference between these examination methods and use them more precisely. If these methods are reliable enough, the quality of the roads could increase significantly, and the cost of the installation and examination of the asphalt layer would decrease significantly.

1. LITERATURE REVIEW ON THE ASPHALT PAVEMENT LAYER QUALITY PARAMETERS

1.1. Asphalt Layer Installation Process

The asphalt layer installation process consists of several major parts: hot-mix asphalt (HMA) manufacturing in the asphalt production facility, transportation of HMA from the facility to the site, asphalt layer paving, compaction and quality assurance afterwards.

Asphalt mixtures, designed for a specific construction object, are made in the HMA production facilities. There are two types of these facilities: batch and drum plants. In batch plants, the HMA is prepared in several separate actions, and the model of the plant is not to store the HMA but prepare it by demand. In drum plants, the HMA is prepared in a continuous process. In comparison, the drum plant produces a higher amount of HMA than the batch plant for the same amount of cost, but the quality of asphalt mixtures is relatively the same. Usually in asphalt production facilities, the temperature of HMA is set depending on the distance between the HMA factory and the site (Roberts et al., 1996).

After the production of HMA, it has to reach the construction site. This process includes truck loading, transportation to the construction site, and unloading to the paver bunker. To avoid particles segregation, the HMA is usually loaded by several smaller masses onto the truck trailer bed. To avoid drop of the temperature of the HMA, the transportation part is crucial, and this process should take as little as possible time by choosing the shortest and fastest route to site, additional temperature protection equipment, etc. When the truck arrives at the site, the HMA should be unloaded to the paver bunker immediately to ensure the suitable HMA temperature for paving, but sometimes due to an unpredicted traffic situation in the route or paving speed, the qeud of trailers forms at the site (Roberts et al., 1996).

When HMA arrives at the construction site, in most cases, it is unloaded directly to the paver (see Fig. 1). After the HMA is unloaded into the paver bunker, the HMA is guided by conveyor belts from the front to the back of the paver. In the rear part of the paver, screed is located, which is responsible for the right profile, thickness, width, and initial compaction forming (Roberts et al., 1996). The basic scheme of a screed is shown in Figure 2. Several factors of the screed could affect the asphalt layer thickness and smoothness: paver speed, amount of material in the paver, tow point elevation, and the screed angle (TRB, 2000). Several automatic solutions are presented for the automatised screed control (see 1.3. subchapter). In some cases, with the pavers, material transfer vehicles (MTVs) are used, like in Figure 3. MTVs are used for windrow elevator purposes, for assurance of additional surge volume or remixing (for the paver, it is advantageous, because it allows the paver to operate without stopping, it minimises truck waiting time at the paving site and could minimise aggregate segregation and temperature differences by remixing the HMA) (Material transfer vehicles, 2020). In the study conducted in 2017, in addition to other parameters, the impact of the use of MTV in the asphalt layer installation process was investigated and the results showed that the temperature segregation of HMA changes from 99% to 4% (without and with MTV).

Fig. 1. Asphalt paver

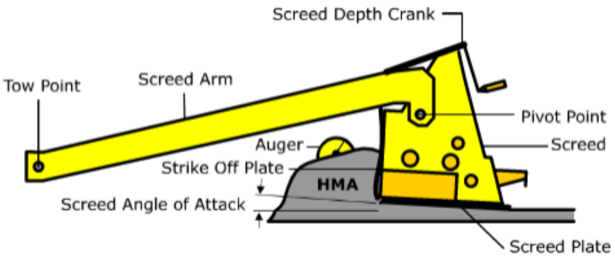


Fig. 2. Screed components

Fig. 3. Material transfer vehicle (MTV)

Fig. 4. Steel wheel roller

Compaction is the process of the asphalt pavement installation in which the air voids in an asphalt mixture are reduced and the aggregate particles are placed more closer to each other by using external forces and mechanisms on the building site, such as steel wheel rollers (see in Fig. 4). This reduction in air volume in the asphalt mixture results in a corresponding increase in its density (Roberts et al., 1996). Further explanation about factors that could affect asphalt layer compaction level, what affects compactions to design life of the road, and requirements for compaction are mentioned in 1.2.1. sub-subchapter.

After completion of the asphalt layer, quality assurance must be foreseen to ensure long-term road quality. Quality assurance is divided into three major parts: quality control, independent assurance, and acceptance. Quality control is carried out by the owner or the contractor in the process of installation. It is often called process control. In this phase, the contractor should provide some measurements to have real-time data of the quality parameters, not only after the end product is made. After the contractor decides that the product is of good quality, the independent assurance phase is foreseen. In this phase, third party, which is not included in process control and acceptance phase, are taken into the process. After sampling, testing, and other laboratory methods obtained on the specific road section, third parties make their conclusions about the results of the quality parameters of the freshly paved asphalt pavement layer. After the process control and independent assurance phases, acceptance starts. For acceptance of the road section, prior the design and constructing phases, precise specifications should be determined, which will be followed throughout construction and assessed for compliance after. Usually, these specifications are regulated by national regulations regarding the construction works, materials, and quality (Transportation Research Board, 2009). Precise specifications, quality assurance parameters that could affect asphalt pavement layer quality, and tolerances for their installation are provided in the 1.2. subchapter.

1.2. Asphalt Layer Installation Quality Parameters and Requirements

1.2.1. Asphalt mixture compaction

Compaction could be affected by (Beainy et al., 2014):

- asphalt mixture materials characteristics, such as aggregate particle size, shape, volume or asphalt binder chemical, physical properties, and the amount of it in the mixture;
- environmental factors, such as ground and air temperature, wind speed;
- construction factors, such as steel wheeled rollers type, compaction speed, timing, number of passes through the specific area of asphalt pavement.

Compaction results are expressed in percentage in comparison with several benchmarks (Hughes, 1989):

- The percentage of theoretical maximum density, which is commonly decided to be 100%, which means that air voids are eliminated in the asphalt mixture.
- Percentage of the density determined in the laboratory, when the desired compaction is reached in the asphalt mixture design stage in the laboratory.
- Percentage of a control strip density, where an asphalt pavement section is installed with desired compaction and used as a benchmark for measurements.

Compaction (air voids) results could be mearused by destructive or non-destructive methods. Today, the commonly used core extraction method (see Figure 5) is destructive, because after the core extraction holes are left, which are usually filled with cold asphalt mixture. This mixture cracks during the time more quickly than surrounding asphalt pavement and potholes appear at these locations. Also coring method is expensive and time-consuming, but the measurement results are the most accurate in compasiron with other methods (Zhao and Al-Qadi, 2019).

Fig. 5. Cores extraction method

Non-destructive testing (NDT) methods at the moment are in testing phase, to ensure full accuracy of the results. One of the NDT devices is nuclear density gauge (NDG), which sends gamma rays through the asphalt pavement layer and from the rays that come back after some time, the device calculates the compaction level (see Figure 6). The main disadvantage of this technology is the necessity of calibration of the specific mixture core. Also, with this technology, only asphalt pavement layers with thickness in the range of 25 to 100 mm, could be measured (Maritime Services, 2015). Another NDT device could be determined as an electromagnetic pavement quality indicator (PQI). PQI works in a similar way as NDG, but not with nuclear particles, but with electromagnetic waves, which is less harmful to humans (see Figure 7). These two methods have the same disadvantage as the core method, that density is measured at some specific points of the section, but not the entire length of the section with specific asphalt pavement mixture. The last method from the NDT devices list is ground penetrating radar (GPR) technology (see figure 8), which has the least damage to the asphalt pavement, measurements are done quickly, cheaply, and are proceeded across the entire length.

Fig. 6. Nuclear density gauge (NDG)

Fig. 7. Pavement quality indicator (PQI)

Fig. 8. Ground penetration radar (GPR)

of the road section (Kassem et al., 2016). Measurements could be done with all thicknesses of the asphalt pavement layers and, most importantly, could be proceeded at speeds up to 80-100 km/h (Saarenketo, 2006).

The analysis was performed, and comparison were made of NDT with a core method. Analysis showed that PQI is the least reliable technology and the presence of moisture in the asphalt mixture has a negative effect on the results of density measurements. Correliation between the NDG and core results is better than PQI, but the necessity of calibration, risk of radiation, and the technology of measurement proceeding at the specified spot makes this method less reliable. The most reliable results of NDT were showed by GPR technology, but the same issue as in PQI was detected – the negative effect on result due to moisture in some of the test points (Baltrušaitis, 2022; Baltrušaitis et al., 2022)

According to many studies by scientists, the void content in the asphalt mixture can cause the following errors (Beainy et al., 2014):

- decreased stiffness and strength of the pavement layer (high void content);
- reduced fatigue life (the higher the void content, the shorter the pavement fatigue life);
- faster ageing, decreased durability (pavement performance is better with the low level of void content);
- raveling (it appears with a void content of 8% and more in the mixture);
- rutting (reduction of air voids in the wheel trajectory of traffic)
- moisture damage (in the mixture with high void content, water could easily enter the mixture and when the temperature drops below 0 °C, the water turns into the ice, the volume of the water/ice expands and breaks the compacted asphalt mixture).

For asphalt base layer from asphalt concrete mixtures where the largest particles are fr. 22 and fr. 32 the compaction degree must be not less than 97% and for mixtures with fr. 16 biggest particles – 96%. For asphalt binder layer from asphalt concrete mixtures where biggest particles are fr. 22 and fr. 16 the compaction degree must be not less than 97% and for mixtures with fr. 11 biggest particles – 96%. For asphalt wearing layer from asphalt concrete mixtures where biggest particles are fr. 8, fr. 11 and fr. 16 the compaction degree must be not less than 97% and for mixtures with fr. 5 largest particles – 96%. Air void content for asphalt mixture with fr. 16 biggest particles and for mixture AC 11 VS must be 6,0%. For AC 11 VN, AC 11 VL and asphalt mixtures with fr. 5 and fr. 8 biggest particles air voids content must be 5,5%. For all crushed stones and mastic asphalt mixtures, the degree of compaction must be 97% and the content of air voids should not exceed 5%. For porous asphalt mixtures, the degree of compaction must be 97% and the content of air voids must be between 22,0 and 28,0% of volume. For the asphalt layer base coating, the degree of compaction must be 97% and the air void content – 6,0%. For pedestrians and bicycle paths with this type of asphalt, there is an exception to reach 96% compaction degree. In the special specifications of the technical task, the customer has the possibility to ask the contractor for the 99% compaction degree for all types of asphalt mixtures and layers. For the compaction degree measurements, 3 samples must be taken from the paved asphalt area of 7000-9000 m^2 (ĮT ASFALTAS 08, 2009).

1.2.2. Asphalt mixture temperature

At the process of production

In the process of HMA production, temperatures must not exceed the maximum limit values according to the national regulation because it could affect the chemical and physical properties of the HMA and separate aggregates in it. In Lithuania, the maximum temperature values in production facility for asphalt concrete (AC) and for crushed stone and mastic asphalt (SMA) are 170–190 ºC (depends from the type and brand of the binder), for mastic asphalt (MA) are 230 ºC and for porous asphalt (PA) are 170 ºC (ĮT ASFALTAS 08, 2009). The temperatures could be lower at the truck loading time, but it should be hot enough to reach the construction site at a proper temperature.

Separate requirements are stated for the binder storage and the temperature of the binder should not exceed the maximum values, which for roads bitumen are 170–200 ºC (depends from the brand of the binder) and for polymer modified bitumen (PMB) are 180–190 ºC (depends from the brand of the binder) (ĮT ASFALTAS 08, 2009).

At the process of transportation

For a better design life of asphalt pavement, it is necessary to obtain a high temperature from the asphalt plant up to the compaction process. After several different studies conducted, it was obvious that most of the temperature loss of the HMA was generated in the transportation process (Dzhabrailov et al., 2020). This part of the asphalt pavement installation process is the most crucial part for future inventions and research. In the previous studies were concluded, that several measures could be taken into account, as the main reasons of this loss of heat in the HMA (HMA Transport):

- distance from the HMA production facility to the site;
- weather conditions on the route (rain, wind, night time with cooler temperature);
- traffic situation on the route to the site;

- forming queue to the paver due to the wrongly predicted time of arrival at the site or due to the wrongly calculated speed of the paving process;

There are several ways to avoid these factors or to minimise the effect for the HMA temperature:

- minimisation of the route distance (possibility of choosing the nearest HMA production facility, using navigation devices and applications for the setting of fastest possible route) (Dzhabrailov et al., 2020);
- truck trailer bed insulation (adding additional material to the construction of the trailer, for better heat resistance sideways from the trailer bed) (HMA Transport);
- additional tarp over the trailer bed (tarp above the trailer bed provides additional insulation and protects the HMA from rain and wind, which decreases heat in the HMA very significantly; see Fig. 9) (HMA Transport);
- the HMA unload procedure at the site should start immediately after the arrival of the truck (this minimises the waiting and cooling time for the HMA, while the truck stands in the queue) (HMA Transport);
- production of hotter HMA in the HMA production facility (this allows one to reach the site with the required temperature of the HMA, even though the temperatures dropped in the transportation process) (Dzhabrailov et al., 2020).

The study by the Quality Improvement Committee of the National Asphalt Pavement Association (NAPA) shows that the HMA surface temperature of the load with tarp decreased slower than the load without tarp, but the temperature at the 100mm depth of the HMA was almost equal. That means that additional insulation measures only help to avoid the top layer of the HMA to form into a crust, which is presented in Figure 10 (Minor, 1980).

Fig. 9. Truck trailer with tarp above the trailer bed

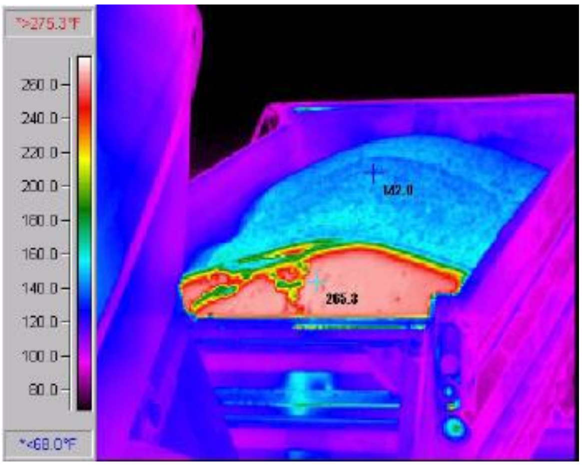


Fig. 10. Difference between HMA temperatures in the top layer of the load and in the core part of the load

In the process of transporting HMA, temperatures must not exceed the minimum limit values according to the national regulation, because they could affect the chemical and physical properties of the HMA and the separate aggregates in it. Also, too low temperature has major impact for asphalt layer paving and compaction processes. In Lithuania, the minimum temperature values at the time of truck unloading to paver bunker for asphalt concrete (AC) and for crushed stone and mastic asphalt (SMA) are 130–150 ºC (depends from the type and brand of the binder), for mastic asphalt (MA) are 200–210 ºC and for porous asphalt (PA) are 140 ºC (ĮT ASFALTAS 08, 2009).

At the process of paving

When truck with loaded HMA arrives, the paver bunker is filled with HMA and the paver starts to distribute all aggregates and particles in the even portions, as the new pavement layers thicknes and width are set to be after paving. If the shipped load of HMA has some areas of cool HMA, the paver will not remix it, and the spots of cooler asphalt pavement layer will appear in the fresh asphalt pavement layer (see Fig. 11). These spots are susceptible to premature failure by cracking or raveling, to water intrusion due to increased permeability, and these areas are with low density. This process is called HMA temperature differentials (Muench & Willoughby, 2006; Willoughby et al., 2001).

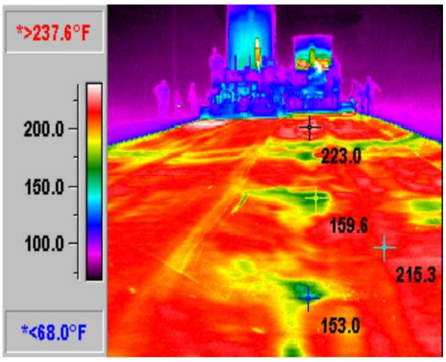


Fig. 11. Infrared image of cooler asphalt layer spots

After these spots of cooler HMA are layed, the only option is to find those spots with infrared camera and foreseen harder compaction procedure in these exact locations, while the HMA has not reached critical temperature, from which the compaction process will have very small impact. In these cool HMA spots, was registered higher air void content and smaller density after the compaction, because these spots are very hard to compact(Muench & Willoughby, 2006; Willoughby et al., 2001).

There are three major measures to prevent this error from occurring in the asphalt layer to happen(Muench & Willoughby, 2006; Willoughby et al., 2001):

- prevention the HMA load crust form forming in the truck trailer (if the load of HMA would reach the paver bunker with the equal temperature in the whole HMA load, the cooler spots will not be layed on the asphalt layer);
- remix of the HMA at the site before it is loaded into the paver bunker (in this process, the HMA will not get hotter, but the temperature will be unified throughout the load and the compaction will be equal at all spots of the asphalt layer);
- harder compaction in the recorded cooler HMA spots (if rollers will approach these spots first and drive through them more times than in hotter places, the asphalt layer will be compacted almost equal).

The requirements for the temperature of HMA in the paving process are not clearly stated, but it should be the same as in the transportation process and should not exceed the minimum values (ĮT ASFALTAS 08, 2009).

At the process of compaction

For equal compaction through the all-road section, the asphalt layer temperature must be equal, because compaction gets less fast and efficient, when layer temperature drops and at some point, it stays stable and no matter how many rides steel wheel rollers do at the same spot, the compaction will remain the same. Parker (1959) performed a study and compared samples compacted at 275 ºF (135 ºC), at 200 ºF (~ 93 ºC) and at 150 ºF (~ 65 ºC). The second specimen contained more than double the amount of air voids than the first, and at the third one, the air void content quadrupled. The study indicates that the majority of compaction should be made before the temperature reaches 225 ºF (~ 107 ºC) and while the mixture is still in a plastic state (Parker, 1959). In the studies of the optimal compaction temperature of asphalt for installation, results show, that this temperature is in range 140–157 ºC. At these temperatures, the nominal number of steel wheel rollers crossings were the lowest, that means, the compaction degree is reached much faster, than in lower temperatures (Bašić et al., 2021).

In other studies, conducted, were performed compaction in different temperatures and the results showed, that value of air voids in asphalt layer changed from 3.5% to 4.0% while temperature was changed from 140 to 100 ºC accordingly and at 70 ºC compaction temperature it reached 6.4%. Marshall stability value at 140 ºC compaction temperature was 55% higher than at 70 ºC (10% – 110 ºC; 40% – 90 ºC). The Marshall stiffness value was significantly affected by the temperature of compaction less than 100 ºC, while in the range 140–100 ºC the change was not that significant. Studies also showed that the minimum compaction temperature to obtain a compaction degree greater than 97% is 100 °C. Additionally, the texture of the asphalt layer was significantly affected by the compaction temperature, due to the aggregate segregation that occurred at a low temperature of paving and compaction. The author of the study recommends that the minimum allowable temperature for compaction must be not less than 110 °C to obtain good and comfortable asphalt layer surface texture and compaction degree (Youness Ahmed, 2005).

In Lithuanian legislation, there are no strict requirements for asphalt compaction temperature, but in order to reach required compaction degree (see in 1.2.1. subchapter), the contractor should evaluate the right asphalt layer temperature before the compaction process begins.

1.2.4. Geometrical parameters of asphalt pavement layer

Cross-slope

According to Lithuanian legislation, the cross-slope for asphalt pavement road must be equal to 2.5%, except in the situations of superelevation (where slope can be increased to 4.0% and in exception to 6.0%). Additionally, in the road sections where the superelevations change from -2.5% to 2.5%, a longitudinal slope of not less than 0.3% must be ensured for the water treatment (KTR 1.01:2008). This requirement is set because of better water treatment from the road to ditches or drainage systems, because if the slope is smaller than 2.5% from the cross-sectional point of view, the water could stay on the surface of the pavement and penetrate other layers of pavement construction. In the process of construction and quality assurance, these slopes are measured by the contractor and third-party laboratories. Measurements are carried out at an incremental distance of 100 m or less. The installed cross slope of the asphalt base layer is considered acceptable if the layer top elevations have a difference that does not exceed 2 cm compared to the design project. Also, for the acceptance of works, cross slopes of all asphalt layers (base, binder, and wearing) after measuring the values must not exceed ±0.5% from the design project values (ĮT ASFALTAS 08, 2009).

Layer width

Asphalt pavement layer width is not that strictly regulated because it depends on the importance, function, category of the road, and traffic intensity in the road section. All road width requirements are provided in the road technical regulation KTR 1.01:2008. However, road construction work acceptance measurements are performed, and the result values of the layer width must not exceed ±5 cm from the design values. The edge of the layer must be smooth and straight in visual terms. These measurements are made at not less than each 100 m (ĮT ASFALTAS 08, 2009).

Layer roughness

Pavement roughness, also known as smoothness, is the level of road irregularities on the pavement surface. Mostly it affects driving comfortability, but also it influences fuel consumption and road maintenance costs. Today, road roughness is indicated by the International Roughness Index (IRI) method, which was developed by the World Bank in the 1980s (Arhin et al., 2015). The roughness measured by IRI is expressed in units of metres per kilometre (m/km) or micrometres per metre (mm/m). The roughness is calculated by taking the accumulated suspension motion of standard vehicles (recorded at a speed of 80 km/h) and dividing by the distance travelled by the same vehicle during the measurement. Road roughness depends on asphalt layer mixture materials, their structure, construction work quality, and road usage after construction (Mielonas, 2014). The main focus of this thesis will be on the quality of construction work for the road roughness and the automated registration of it.

For the acceptance of the construction works in Lithuania, the requirements are presented in rules of installation of asphalt layers ĮT ASFALTAS 08. The roughness in the cross-sectional and longitudinal directions are measured by a 3 m length ruler and according to the LST EN 13036-7 standard. The measurements are performed in each lane at an incremental distance of 50 m. Cross and longitudinal slopes for the roughness measurement must be eliminated. Surface irregularities, which do not exceed the limit values (presented in table 1), but repeat at regular small distances, are also counted as defects of the pavement layer. Pavement roughness, when measuring by the IRI method, must not exceed limit values:

- highways (where the speed limit is 110-130 km/h) – 1.0 m/km;
- other highways (where the speed limit is 90 km/h) – 1.5 m/km
- regional roads – 2.0 m/km
- district roads – 3.0 m/km

Table 1. Layers, installed with a paver, roughness limit values (ĮT ASFALTAS 08, 2009)

Layer, on which the new layer will be installed	Roughness, measuring with 3 m length ruler, mm			
	Asphalt base layers, asphalt base-pavement layers	Asphalt binder layers	Asphalt wearing layers from mixtures	
			AC, SMA, MA	PA
1. Layer without binders	10	-	-	-
2. Base layer with binders, asphalt base layer	10	6	6	-
3. Asphalt binder layer	-	-	4	3

Layer thickness

Asphalt layer (base, binder, wearing) thickness is one of the most important features for the pavement construction lasting for the whole design life. The structural condition and bearing capacity of pavement depend on many factors, and one of them is layer thickness (Vaitkus et al., 2020). Only strictly calculated and designed asphalt pavement layer thickness can assure that pavement construction will reach the design life. With greater asphalt layer thickness, less strains occur in the bottom of the layer due to vehicle axle load (Cao et al., 2022). But every centimetre of asphalt layer addition is very costly, and a lot of research tries to evaluate the golden middle between the quality of pavement construction and cost estimates.

In Lithuania, at the design process, the designer must calculate the design load A (from annual traffic flow data) to choose the right pavement construction class, which also includes the thickness of the asphalt layers, from the road design rules of standard pavement constructions (KPT SDK 19, 2019). At the construction and quality assurance phases, measurements of the thickness of the installed asphalt layer are foreseen. Measurements are processed by extracting cores or with a GPR device. Measurements should be performed at incremental distances of 50 m, but in the core extraction method this distance could be increased to 200-300 m. The thickness of the asphalt layer, which occurred with higher values than in the project, is not considered as a defect, but if the thickness values of the layer are lower than in the project, the minimum limit values are presented in Table 2.

Table 2. Minimum limit values of the layer thickness (ĮT ASFALTAS 08, 2009)

Application	Installed smaller layer thickness limit values, cm					
	Asphalt wearing, binder and base layers together	Asphalt wearing and base layers together	Asphalt wearing layer	Asphalt base-pavement layer	Asphalt binder layer	Asphalt base layer
1. Average value of layer thickness	0.4	0.4	0.4	0.4	0.4	0.4
2. Layer thickness separate value	0.5	0.5	0.5	0.5	0.5	0.5

1.3. Automated Registration of Quality Parameters of Asphalt Layer Installation

1.3.1. Intelligent construction

The intelligent pavement construction system consists of intelligent paving and compaction processes combined and controlled by an intelligent control program. This system is created and being tested to reduce the amount of road workers in construction works. But this system, as well as controlled by human system, must ensure that the installed road section meets the national requirements for asphalt pavement quality (Yuan et al., 2022).

To control the temperature segregation of the asphalt layer, the infrared temperature sensor is installed on the paver to get real-time data of the surface temperature of the entire paving section. In addition, at the same time the paver speed is collected by the global positioning system (GPS). Supervision is carried out in the paver bunker also, where the control system automatically controls the material level of the feeding system and can implement speed for the paving operations due to the amount of material in the bunker. These measurements after collection are sent to the remote server computing centre (RSCC) in real time for analysis, data storage, and paving operation report generation. After analysing the received data in RSCC, the information about needed corrections for the paver are sent back to the paver base station, and it transfers all new settings to the levelling controller of the paver. In the front of the paver inclination sensor is installed for detection of the manholes, surface irregularities, or other disturbancies to ensure that paver body remains at the design altitudes and corrects the suspension elevations. For quality control in the paving process, one of the measuring robots always monitors the specific situation of the paving and reports on the control parameters that meet the design requirements (Yuan et al., 2022).

In the compaction process, one of the key monitoring points is position, which is collected with a high-precision positioning terminal installed in each roller. With this information, the management personnel could monitor, control and plan how many times rollers pass each area and roller real-time speed. In addition, rollers are equipped with infrared temperature sensors for collecting and uploading real-time compaction temperature data. In each roller hardware, design parameters are uploaded before compaction procedure in order to ensure required quality for compaction, layer thickness, etc. For quality control throughout the compaction process despite system self-control, management personnel are in touch with real-time data, and they can change roller settings remotely and on time (Yuan et al., 2022).

'Unmanned airborne infrared detection system' is also one of the intelligent construction parts. This system accurately monitors the temperature data of the asphalt pavement layer and represents it as an infrared image of the surface or even as a thermal image video in real-time. With the help of this system, road workers do not need to manually check the temperature at some selected points or take infrared photos from a very uncomfortable angle. This intelligent construction methodology is being tested in Shanghai Zhujian road reconstruction project at 4.5 cm thickness AC-16 wearing layer installation procedure. To the system are connected 2 parallel working pavers, 2 double steel wheel vibratory rollers, 2 rubber wheel rollers, and 1 double steel wheel smooth rollers. The control platform technology in this system can ensure that the accuracy of the equipment is within 5 cm and the control of the flatness / roughness of the milimetre level (Yuan et al., 2022).

Volvo prepared a system called Pave Assist, which collects data about distance covered by paver, tonnage of paved asphalt, paved area, and CO2 emissions of paver. With such data, construction managers can identify pavers throughput efficiency and use these results for future projects and paving processes. This system collects data real-time and from on-board information and automated reports, which software prepares. All data could be stored and accessed remotely in the cloud, allowing the usage of past results in the future (Volvo, 2022).

Vogele, the Wirtgen Group Company, introduces a new technology called WITOS Paving. It is a digital system that collects real-time data of the paving process, analyses it and represents it directly to the construction company office and on site if needed. It could help to better understand truck logistics from the asphalt factory to the job site, about the asphalt layer temperature, and geometrical properties. After the paving process, the system represents several charts, including the temperature distribution in the asphalt layer (thermal map, see Fig. 12), temperature distribution in trucks, the truck delivery, the waiting, and the loading times. Furthermore, the system represents geometric and statistical parameters of the asphalt layer installed, such as layer thickness, width, amount of material, density and so on. (see Fig. 13) (Vogele, 2023a). The WITOS Paving Plus technology package offers the possibility to plan construction works, follow this plan and deviations from it in real time on site. This package helps to improve the work of the asphalt mixture plant, the transport process of the asphalt mixtures to the job site, the asphalt layer paving process, and to help paver operators adhere to the construction works plan (Vogele, 2023b).

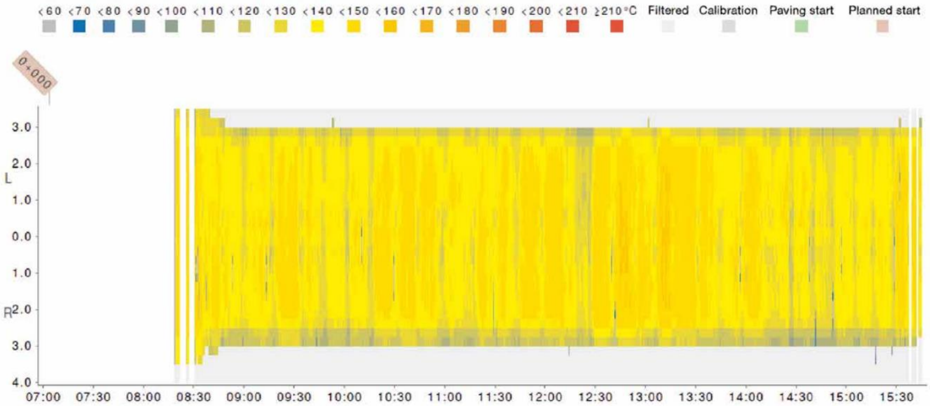


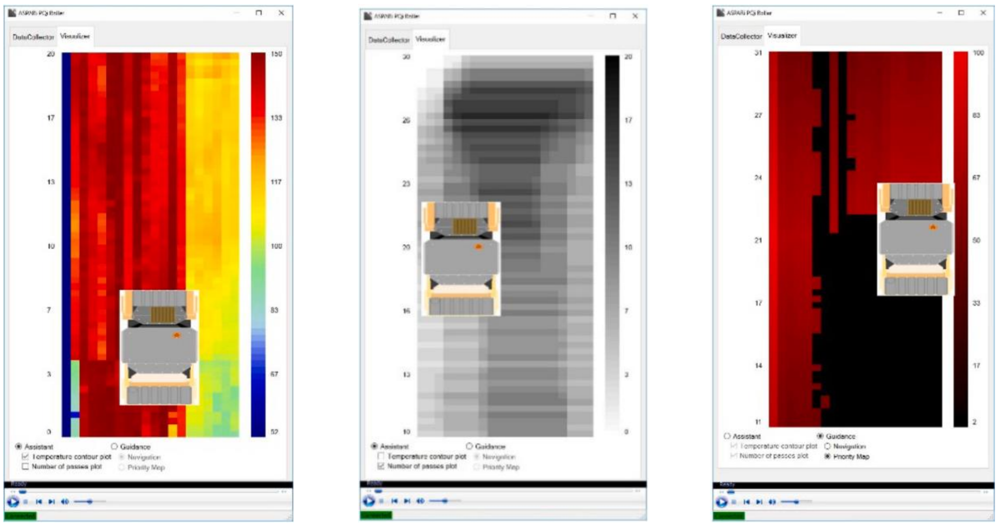
Fig. 12. Thermal map of the WITOS Paving software

Duration:	15.03.2019 07:54 to 18:54
Paving length specified (actual):	- (2198) m
Paving surface area specified (actual):	- (8971) m²
Layer thickness:	4.0 cm
Lorries/number of delivery notes specified (actual):	- (12) Lorries with (37) delivery notes
Quantity specified (actual):	- (952.98) t
Ø Screed width specified (actual):	- (4.08) m
Ø Pave speed specified (actual):	- (4.0) m/min
Ø Laydown rate specified (actual):	- (103.0) t/h
Ø Areal density specified (actual):	- (106.2) kg/m²
CO2:	- kg

Fig. 13. Statistical and geometrical output of WITOS Paving software

1.3.2. Compaction

Nowadays, majority of rollers collect basic data, such as asphalt pavement surface temperature (see fig. 14a) and location or number of passes through the specific spot (see fig. 14b). This information is displayed to the roller operator by the monitors in the cabin, but this information is presented separately. Using separate parameters to ensure equal compaction in the entire road section is a very hard job and depends on the experience and knowledge of the operator. There are some systems in the testing phase to help the operator navigate through the asphalt layer. One of these systems is the compaction guidance system, which combines the temperature and number of passes through specific spot to one map, which shows areas of different importance for compaction (see Fig. 14c). This allows drivers to see where temperature drops more rapidly, but the number of passes through these areas is not reached as required (for optimum compaction; no such requirements are stated in Lithuanian national regulations, but the number of passes to reach required compaction could be calculated empirically) (Makarov et al., 2021).



(a) (b) (c)

Fig. 14. Separate temperature (a), number of passes (b) and guidance system (c) displays

For a clearer understanding of the study and the system, the effective compaction rate (ECR) parameter was introduced. This ratio includes the number of passes that were made through a specific spot at the specific temperature. For this study, the 80% value for passes and 120-150 °C for the optimum temperature range was used, so $ECR_{80\%}$ means that 80% of the total number of passes were made at the specific spot location and within the range of 120-150 °C and this small area, the cell, is decided properly compacted. The case study covered three different scenarios, without any guidance system or display, only with separate temperature and number of passes displays and with a guidance system display. The results of this case study are presented in Table 3 (Makarov et al., 2021).

Table 3. Results of the case study of the guidance system (Makarov et al., 2021)

Number of cells, %	1 scenario	2 scenario	3 scenario
Compacted properly	13.3	22.3	28.7
Under-compacted	26.7	23.3	19.2
Over-compacted	33.0	32.0	39.5

From the results it is clearly visible that the guidance system, which uses real-time temperature and location data, improves the quality of compaction by 115% in total. But it has to be mentioned that this study was conducted only under controlled environment and on small-scale, so results have to be perceived with caution (Makarov et al., 2021).

Also, additional devices for determining the compaction are designed and created, that can registrate all pavement density, not at some local points on the asphalt layer as other non-destructive testing (NDT) methods. One of these devices is created by the GSSI company – PaveScan RDM 2.0. This device is mounted on the cart and has to be driven by human so far, but in the nearly future there are possibilities to make it more autonomous and independant from human being. This device scans top pavement density and its non-conformity, which could be used in quality assurances stages, especially in acceptance stage. This device is more designed to determine the density of asphalt pavement after the compaction process, so it is not very helpful in real-time of asphalt paving process, but it is a step forward in the direction of real-time data registration process (GSSI, 2023).

Intelligent Compaction (IC)

As far as compaction is one of the most important processes of asphalt pavement installation and the degree of compaction is one of the criteria, used for the road section acceptance procedure, innovations try to break through to this part of the road construction works. One of the new systems that is being tested is intelligent compaction (IC). IC is new technology that captures all compaction data – location, time, and settings used for compaction. For IC to work, the steel wheel rollers must be equipped with: accelerometers mounted on the axles of the drums, GPS, infrared temperature sensors, and onboard computers, which can display real-time IC measurements results for the roller operator. IC process output are as follows: IC measurement values (ICMV), roller passes, asphalt surface temperatures and roller settings, such as vibration frequencies, amplitudes and speed (Chang et al., 2014). ICMV are often expressed as the compaction metre value (CMV) or the compaction control value (CCV), where both indicate the stiffness of the asphalt layer and are dimensionless (Nieves, 2014). Several studies have been conducted to evaluate the reliability of the results of the IC system compared to the results of the core density.

One of the first tests of intelligent compaction were held in 2008-2010 in the USA in 16 field projects to determine the correlation between ICMV and core densities. The results of the study showed that correlation is inconsistent due to limited spot tests and different nature of measured properties, for example, mechanical properties compared with material proportions. Also, the ICMV results were compared to the NDG results, and the correlation between them was also very low. After using multi-linear regression, the results of correlation were improved and these analyses showed, that influences of multiple factors, such as machine settings (amplitude, frequency), conditions of underlying layers and HMA temperatures is very high. The conclusions of this study were that IC data can be used to build a compaction curve for a specific material and could be used to identify the optimal number of passes of the roller to prevent under- and overcompaction (Chang et al., 2011).

In the period of 2011-2014, further implementation and testing of IC systems were conducted in several different states and in several different significance road sections, 9 sites in total. Mainly installed and tested were asphalt base layers of different layer thicknesses. For the compaction procedure, IC rollers of BOMAG, Caterpillar, Hamm, and Sakai were used. The main components of each manufacturer roller definition were the same, but each has separate settings, methods, and other specific differences. Each roller is equipped with the manufacturer’s hardware and software, and the output settings differ, and it is very important not to compare two different rollers from the manufacturer in order to provide ICMV data for one road section. Comparison between two different manufacturers' rollers could only be foreseen when seeking the reliability and ICMV variability evaluation of different rollers. Also, ICMV is influenced by the type, weight, vibration frequency, and amplitude, direction, and speed of the roller. Therefore, for the whole IC process, all these operating settings must be kept stable, in order to get legitimate ICMV results. Each testing was performed over a 4-day period, one day before calibrating the GPS devices and pre-mapping the sublayer if possible. For each test two rollers were used, one for breakdown and another for intermediate compaction. After paving, a minimum of two spot locations are selected and measured immediately after the passes of paver, breakdown, and intermediate rollers. The measurements evaluate density (with NDG), surface temperature, and exact locations (with GPS). After the final compaction pass of the rollers, 60 spot locations were selected to proceed final testing, which includes NDG testing, coring (where cores were tested in asphalt laboratories to evaluate bulk densities), GPS measurements, and other tests. All real-time ICMV results are collected in each roller software (of the middle point of the drum axle) and with the help of vendor software, the results are duplicated across the whole width of the drum. All the data from each roller software are exported to external storage in two separate files: all-passes data and final coverage data. All-passes data cover the information of all compaction process, and final coverage data contains only the last pass of the roller information about the final surface (Chang et al., 2014).

NDG measurement results, linear correlation of mean R^2 with breakdown rollers ICMV is 0.6, but with the intermediate rollers ICMV - only 0.3. Therefore, this correlation shows that the compaction process is more efficient at higher temperature. With the knowledge of the correlation of NDG and ICMV results, these real-time data could be used at breakdown compaction for quality control (QC) to maximise the window of opportunity for compaction. However, the specific temperature range depends on the mixture type, layer thickness, and asphalt binder. But the correlation of asphalt core density with final coverage ICMV is weak and the main causes could be the following (Chang et al., 2014):

- the asphalt layer temperatures are in the lower range at the final pass and the asphalt binder viscosity is increasing, which has an effect on the rebound behaviour of the roller drum;
- the ICMV results gained during the breakdown and intermediate compaction procedures, while the finish rollers finished the compaction process, and even though changes in density are not likely to occur, it may affect the correlation between final coverage ICMV and core densities;
- the possible uncertainties of IC data gridding and GPS precision may affect the accuracy of data evaluation.

Analysis shows that even with the same materials, paving equipment, its settings, and the same work force, data from IC equipment vary significantly. This means that the complexity, while seeking to achieve desired asphalt density daily, is very high. According to the study authors, it is not recommended to fully rely on the ICMV result for acceptance, as it does not correlate sufficiently with the density of the asphalt layer core, but it is recommended to require that at least 70% of the compacted areas be compacted with the IC methodology (Chang et al., 2014).

Another way of using ICMV results for acceptance is selecting points for cores extraction from IC made map of compaction degree (see Fig. 15). On the map, which was prepared after compaction, the weakest points of the whole road section could be determined, and cores were extracted at these spots. If the core density meets the requirements at the weakest spots, then all road sections will be of sufficient quality, in case of degree of compaction. If the core density at these spots does not reach the minimum required value, then other points should be selected with higher degree of compaction on the map and after their verification, the areas in which compaction must be corrected are determined more easily. This testing methodology could ensure that in quality control and quality acceptance phases evaluation covers entire road section, not only randomly selected spot locations (Xu et al., 2022).

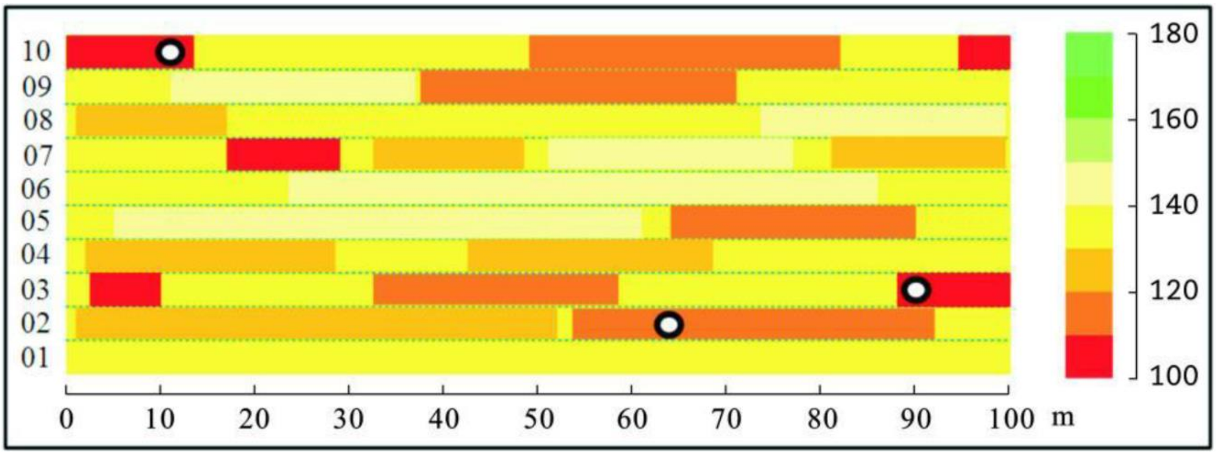


Fig. 15. Combination of continuous and point inspection

At the study conducted in 2017, the results of the IC process were compared to the densities of the core investigated immediately after the paving process. The analysis showed that the correlation between ICMV and core density is equal to $R^2 = 0.62$ and that this correlation could be used to determine the target ICMV for the QC and QA phases. But the correlation between the number of passes that was captured with the IC system, and the core densities was significantly greater with $R^2 = 0.96$. This result shows that well-produced HMA compacted with specific roller at the specific design frequency, amplitude, and temperature could be determined and evaluated only from the number of passes that roller made (Chang et al., 2018).

TopCon introduces new technology for intelligent compaction. Compaction systems C-53 and C-63 are installed in rollers to get number of passes, asphalt temperature, and layer stiffness data in real time and with the option to save them in storage, for further analysis of typical compaction process errors and possible optimisation perspective. The usage of this software could lead to 30% faster compaction works, which reduces CO_2 emissions and risk of under- and overcompaction. The GPS sensors, mounted in the rollers generate the number of passes colourful map for the optimisation of operators work (see in Fig. 16). The temperature sensors, mounted in the rollers, help the operators to be sure that compaction process is proceeded at optimum asphalt temperature. The stiffness sensors help to ensure that stiffness values of the HMA layer meet the requirements after compaction and stop the rollers work immediately when stiffness value reaches required design values. All the real-time data could help contractors to be pro-active and deal with issues immediately when they occur and prevent others from happening, to be efficient - analyse the past compaction data and help operators to avoid repeating mistakes, and to be profitable, when achieving optimum compaction in order to reach quality compaction (TOPCON, 2022b, 2022a).

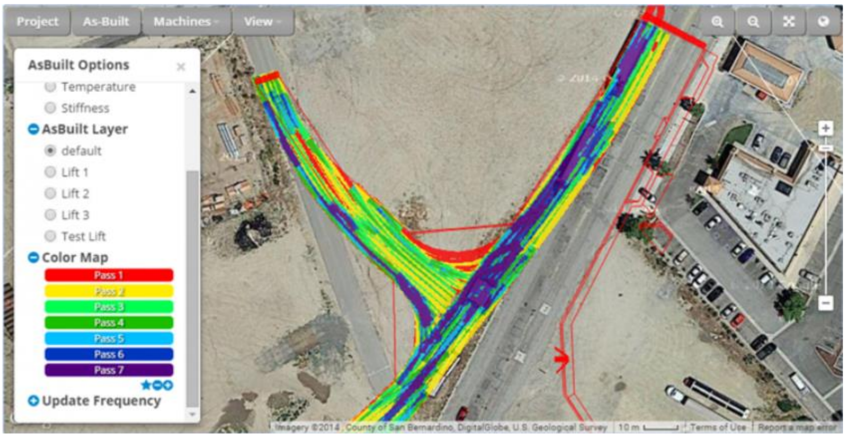


Fig. 16. Number of passes colorful map

It is also worth to mention that benefit-cost analysis was conducted in 2016 in USA, where IC were compared with conventional compaction and their influence on the service life with service costs was determined. So, the construction costs determined in this research were 37% lower with IC compared to conventional compaction for the thick asphalt overlay and 54% lower in the case of a new road construction with IC. These percentages converted to money would be more than 15 thousand dollars savings each year. In addition, what counts for the service life, the road constructed with IC accumulated the result of 26 service life years compared to 10 service life years of the road constructed with conventional compaction (Savan et al., 2016).

In order to compare and collect data in the same system, several countries require to install Veta program in these construction objects, that uses intelligent compaction (IC). This program represents all data in maps, graphs, presents analysis and various reports. It allows construction companies to use different manufacturers rollers, export all data to Veta system and still receive the same output information which is required by the Customer. This unification of the output data could lead to a united regulatory system for IC usage in construction works (Veta, 2023).

Compaction Monitoring System (CMS)

The development of this system is made parallel to the development of intelligent compaction as it is a similar concept to systems. This system monitors asphalt layer temperature, location and movement of the roller, vibration of the roller, and evaluates the compaction effort from these data. To collect such data, GPS radar, two infrared sensors on both sides of the roller, and accelerometer are installed on rollers. This system takes into account the compaction index, which represents the knowledge that at the sides of the wheel of the roller, compaction is made less efficiently than in the centre of the roller (see Fig. 17) (Kassem et al., 2012). When the system collects the number of passes of the roller through the specific spot of the asphalt layer and the temperature of it, it can calculate the compaction effort, in which the compaction index is already included. Currently, this system is more like a data analysis system after construction because it can save all the data and these data could be revised later. But in the future, authors indicate a very likely chance of this system working in real time. For that, roller systems must be connected to each other to calculate the whole picture of the compaction of the asphalt layer (Kassem et al., 2015).

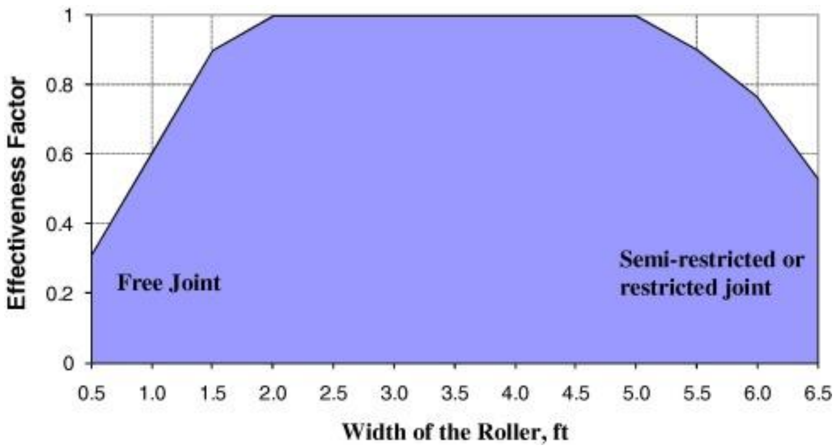


Fig. 17. Compaction effectiveness depending from the width of the roller

Smart Compact

The Wirtgen group company HAMM introduces a new technology called Smart Compact. This is a combination of software and devices in rollers that collect data and set settings for compaction. This system evaluates asphalt temperature and stiffness and selects right parameters of drums and types (vibration, oscillation, or static) for compaction process. The roller operator only specifies which asphalt layer is to be compacted (base, binder, or wearing). This software also detects local weather conditions and can evaluate asphalt cooling behaviour. With respect to the data collected from the asphalt, the system recognises the optimum time for the end of dynamic compaction and turns it off for fuel saving purposes. According to the distributor, the result of fuel savings is 15%. Smart Doc, the application for

Smart Compaction system, prepares compaction maps to show operators, which parts need to be compacted. The system also records the number of passes and after optimising the roller route to avoid double passes, the result is a reduction of 30% of the passes, which reduces fuel and CO2 emissions (HAMM, 2022).

The HAMM company also offers another product called HCQ, which is a shortcut for HAMM Compaction Quality. It is system that works together with WITOS Paving and helps for contractors to do all paving and compaction processes supervised, monitored, and controlled. This system with the help of various sensors can register the stiffness modulus of the layer, which can determine the degree of compaction, and it can also register the temperature of the asphalt layer at the time of compaction. All this information is displayed for the roller driver together with the roller position, number of passes, vibration and its amplitude. The number of passes could be presented separately and together as a whole compaction process, because all rollers have a connection with each other via WLAN. All this information is presented in real-time as compaction process is ongoing and could be collected and analysed afterwards with the WITOS Paving Plus application. This helps to improve compaction processes both in real-time and in planning future construction projects (HAMM, 2023).

Asphalt manager

The Bomag manufacturer introduced a new technology called Asphalt Manager. This system helps operators and contractors reach optimum compaction degree with the highest possible efficiency in fuel emissions and time. With this system, operators are required to choose only the type and thickness of the layer and the compaction procedure is ready to start. This system is equipped with several different sensors and could display to the operator the stiffness, amplitude, and temperature data. The system automatically adapts the amplitude, when the stiffness and asphalt temperature reach certain values to avoid crushing the aggregate. For measuring the compaction parameters, the Evib parameter is presented and measured in real time and displayed to the roller operator (see Fig. 18). It helps the operator supervise the compaction procedure and control the amplitude of the drums. Also, this system automatically matches the direction of vibration to the direction of roller movement, and this prevents the formation of ripples, because no bow wave is generated. When standing still, the system automatically adapts and switches to horizontal vibration to prevent drums from digging into the layer and to prevent restarting the roller, which could create wave on the layer surface (BOMAG, 2022).

Fig. 18. Roller operator display with Evib, temperature and amplitude parameters

<u>*Ground Penetrating Radar (GPR)*</u>

A study was conducted to determine nowadays used non-destructive testing (NDT) methodology and devices fro compaction, that registers all data in site at the moment of compaction. Despite several already mentioned and described devices in this thesis, this article presents ground penetrating radar technology that could be used in the future. This device collected density results were compared with core density and has shown a significant correlation. GPR could be used in several ways (mounted on the paver, mounted on the steel wheel roller, mounted on the cart, mounted on the trail for the car, mounted on the drone) and in several situations (at the moment of compaction, immediately after compaction, or after some time from compaction). Mounting on the paver could be seen as not that efficient installation and result accumulation way, because everything depends on angle of installation, pavers always stay in the same position in accordance with the asphalt layer. Mounting the roller could be the most convenient and efficient way, but roller vibrations must be eliminated to obtain exact asphalt density results at the time. Mounting of the GPR mounting on the cart or on the trailer is possible only in situations where measurements are conducted after compaction, because it requires additional vehicles and human work. GPR mounted on drones are currently tested technology, and it has major disadvantage as it very depends on weather conditions, and it is suggested to use this technology only in fast and large territory coverage asphalt pavement density measurements (Wang et al., 2022).

1.3.3. Temperature

For the compaction process, asphalt temperature data are very important and could lead to more efficient compaction by operators, who receive such data. However, the asphalt surface temperature depends on the weather conditions and may cool at different speeds depending on the weather. To ensure the temperature data and the prognosis on how the temperature could change due to weather, the automated temperature unit (ATU) was invented. The ATU consists of the infrared (IR) camera, a measurement device with termocouples, and a processing unit. IR camera and thermocouples could be used at any location after the paver, on the side of the road. After the paver passes through the ATU station, thermocouples must be injected into the asphalt layer and an IR camera pointed to the area in which temperature needs to be determined. IR camera immediately detects highest and lowest temperature points in the scope of lens, and thermocouples give in-asphalt temperature back to the processing unit. The processing unit uses the received data from the IR camera and thermocouples and calculates the prediction of material cooling. But the prediction is not that complicated and does not include variable weather conditions, only pre-paving selected cooling curve model. But these measurements are made continuously and on real-time, so the cooling curve could be modified by the real-time temperature-changing trend (Vasenev et al., 2012).

In the study conducted in period 2007-2008 three different IR cameras and measurement methodologies were tested to determine the most efficient way of continuous temperature measurement. The first case study was conducted on Highway A35 section in the Netherlands in April 2007 with a handheld IR camera. This scenario needs to be coordinated and proceeded by humans and IR cameras vision area is not that wide and angle of images is also small, because of workers standing on pavement and taking pictures. The second case study was conducted at Aziehavenweg, Amsterdam, in July 2008 with the industrial IR camera mounted on the paver. This camera takes images every 5 seconds. Due to the narrow angle of view of the optical lens, the distance of images was 17 m from the camera and paver, in order to obtain the full view of the road section (see Fig. 19). The third case study was conducted at Heerenveen in November 2008 with the IR line scanner mounted on the paver. This scanner was mounted at the same location as the IR camera in the second study, but the lens angle of view was significantly wider, which led to a distance reduction behind the paver to take images immediately after the screed. Images with the scanner were taken every 3 seconds, which was more of a challenge than with the IR camera. The results of asphalt pavement surface temperature were more precise with the IR line scanner mounted on the paver, due to the optimised angle of the camera, fully automatization and no need of human supervision, and more detailed images due to the often-taken images. Parallel with these studies, in-asphalt temperatures were also measured and compared with surface temperature measured with IR devices. The results of the comparison are presented in Fig. 20. The correlation between these temperatures was strong and most of R^2 values were above 0.9. These results open up the opportunity to use surface temperatures, measured with IR devices, as reliable indicators of the in-asphalt or core temperatures (ter Huerne et al., 2009).

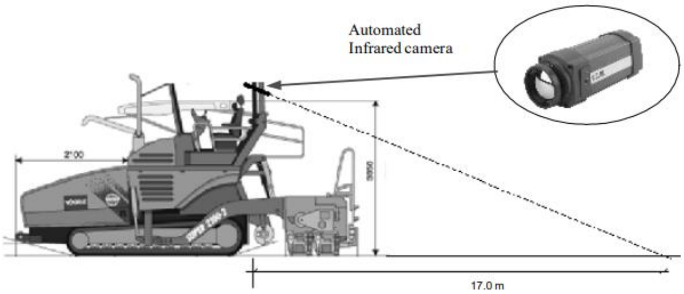


Fig. 19. The automated IR camera mounted on the HMA paver

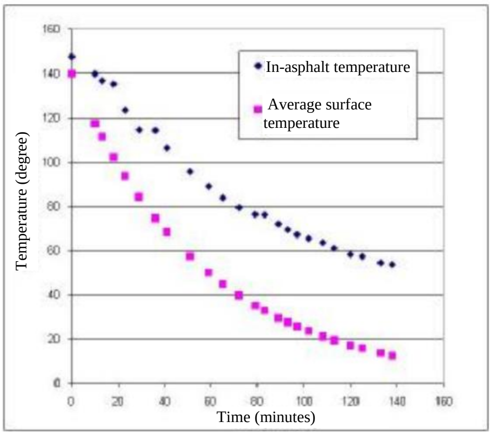


Fig. 20. Comparison of surface and in-asphalt temperature

Vogele presents a device, called Vogele RoadScan, which uses the IR line-scanner mounted on the paver. Due to wide angle, this device could measure temperature at 10 m width road section and scan asphalt layer surface temperature immediately behind the screed (Fig. 21). RoadScan has a GPS tracer installed inside, so an accurate location is provided for each measurement to analyse the data after paving. Supervision of weather conditions is also possible, including wind speed, direction, air pressure, and humidity. Measurement results are displayed in 25x25 cm tiles, each of these tiles containing up to 16 measuring points. The measured temperature tolerance for this device is only ±2 ºC. All recorded temperature data could be stored in a database to analyse after the paving process, but also it is displayed in real time for the paver operator and could be connected to the roller operators to ensure quality compaction (VÖGELE, 2022).

Volvo prepared a system called Pave Assist, which captures asphalt layer surface temperature for evaluation of the asphalt thermal quality and identification of process issues, which could be corrected in real-time. Also, this temperature detection system helps for the compaction process to ensure an optimal temperature range for compaction. This system also observes weather conditions to predict changes in weather and surface temperature of the asphalt layer. With this type of data, construction workers can adapt paving and compaction procedures to the upcoming weather conditions (Volvo, 2022).

Fig. 21. Temperature registration behind the paver with thermal camera

The Estonian company, called Teede Tehnokeskus, has another device or software for offer, called TGS Pavement. This equipment scans temperature and its uniformity of the asphalt pavement layer that has been paved immediately after the paver (see Fig. 22) and represents these data on real-time in situ and in some background factory or company facilities or even for the Builder. This measurement helps for the Contractor to react in real time with the compaction processes if some cooler spots are located, and also for the Builder it is sufficient data for quality assurance phase. This technology works consistently as the paving process is ongoing to provide continuous data flow for the interested parties. This device is compatible with all types of pavers and also offers a data collection possibility to analyse these data after construction works. This TGS Pavement methodology was created on the basis of Finland and Sweden experience. Furthermore, this device could be used for bonus motivational systems (further explained in subchapter 1.4) (Teede Tehnokeskus, 2023).

1.3.4. Roughness

For automated roughness measurement, the TRRL (Transport and Road Research Laboratory) high-speed laser profilometer could be used. This system consists of 4 laser triangulation transducers which are placed along a 5 m long trailer, which is towed by the vehicle. At the process of movement and measurement, the leading laser detects the elevation, and other sensors are placed as the references, so there is no need for an inertial sensor for referencing. Several systems were tried to eliminate the trailer from this measurement, but the results were too dependent on the mechanical properties of the vehicle. The origins for this profilometer date back to 1966, but nowadays a lot of different specifications for this device are implemented to reach high speed to avoid disturbing traffic flow for measurements. Kilic

& Hilsmann (2016) conducted research on testing this device at high speed. The accuracy of measurement, in comparison with reference measurements made with ruler and level, was: 7.92 mm for 100 m wavelength, 2.85 mm for 30 m wavelengths, and only 0.44 mm for 3 m wavelengths. Although it should be mentioned that these tests were carried out not on the highway, so measurement results could vary depending on speed and road quality, because sudden braking or driving through the bumpy section has a major impact on the results (Kilic & Hilsmann, 2016). In another study 4 different devices were compared with each other for the correlation between them detection: USF Walking Profiler, FACE Dipstick (the standard device for calibrating roughness measuring systems), ICC Walking Profiler and FDOT High-Speed Profiler. All devices were tested for at least three repeat runs. Based on the analysis results, it was stated that the correlation between all these devices was good. But these tests were conducted with limited roughness of the road section, for a wider analysis, worse roughness conditions recommended to be applied at the tests (Lu et al., 2003).

Another methodology for IRI measurement were presented by Zhao & Wang (2016). They tested the dynamic tyre pressure sensor (DTPS) with an axle accelerometer for IRI measurements. This system includes DTPS mounted on the right rear tyre, axle accelerometer, mounted on the right rear axle, GPS, and camera as shown in Fig. 22. During the movement of the vehicle, DTPS measures the dynamic pressure inside the tyre, which varies due to tyre and road interactions, and axle accelerometer measures vertical acceleration of the rear axle, camera takes surface images every 1.3 m and GPS records exact vehicle location every second. All these data are sent to the remote data centre and stored in the database. This measurement methodology was validated by a 2014 MassDOT certification test on a runway at New Bedford Airport in Massachusetts. Compared to the measured and calculated IRI by this methodology, 2012 measurements data with laser profilometers with accelerometers were received from MassDOT. The speed limit for measurements with this methodology must be between 24 km/h and 96 km/h. The results of this study are presented in Table 4 (Zhao & Wang, 2016).

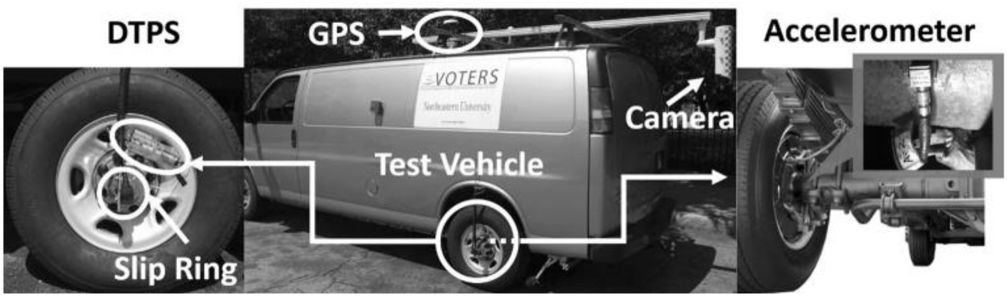


Fig. 22. Sensor configuration on the test vehicle

Table 4. Comparison of IRI results at different speeds for multiple urban roads (Zhao & Wang, 2016)

Road No.	Distance, m	IRI (m/km) by MassDOT 2012	IRI (m/km) at different speeds (km/h)			
			40	48	64	80
1	73	2.67	4.19	4.17	3.77	5.51
2	201	3.11	6.85	7.00	7.01	6.84
3	90	3.98	5.48	4.79	6.46	5.41
4	70	3.25	4.65	4.72	4.33	4.87
5	91	2.94	2.65	3.21	3.40	4.40
6	276	3.00	4.61	4.16	5.45	6.23
7	100	3.33	3.54	4.37	4.63	5.94

From the results of IRI measurements, it is visible that not all measures met at the same road sections, but with different speeds were equal enough, this happened due to damages in road surface and human factor when driver cannot repeat exact same driving line as in previous run. The comparison of results with the MassDOT data received is not very reliable due to the time period between the initial measurement and the study conducted, because at a two-year period, the asphalt layer surface could be damaged very severely. But research showed that this system can be used for IRI measurements, but the accuracy of the results must be examined and tested more (Zhao & Wang, 2016).

For the measurement of IRI, the autonomous robot P3-AT was tested. This robot was equipped with odometers, computer, CCD laser and SICK laser ranger finder to perform the collection of longitudinal profile data and calculation of IRI. The tests were carried out indoors with a smooth and uniform 50 m test pavement section. The IRI results of the measurements made with the robot (1.09 m/km) were compared with the results of the ARRB walking profilometer (1.11 m/km). But the smooth and short track could have a major impact on the correlation of the results. For the current robot specification, there is no accelerometer mounted on it due to the smooth and level track, but for real tests on the roads, the accelerometer could be installed on the P3-AT robot. For future studies there are possibilities for inertial navigation system using an inertial measurement unit and GPS, implementation for more accurate determination of robot position and orientation. This system also could detect accelerations and angular velocities and detailed pavement information, such as grade, cross fall, could be provided for the inspection and construction QC with QA phases (J.-R. Chang et al., 2009).

1.4. Motivational Systems

Several European countries are trying to implement and create bonus systems for contractors to be motivated to register automatically asphalt installation quality parameters. One of these countries is Estonia. They created a bonus system in 2018 for contractors with an example of Sweden and Finland systems, which allows one to get a reward for an extra effort that has been made for quality improvements of the road network. Estonian construction companies are giving only positive feedback about this bonus system and at the moment there are 100 contracts, which consists of 600 km roads in Estonia, that use or use this bonus system from its beginning in 2018. If the quality of the pavement installation is higher than the minimum requirements, then the contractor can earn a bonus. In general, bonuses are up to 5% of the contract fee, depending on the type of construction works: 5% for the asphalt layer overlay, 2.5% for the pavement reconstruction and 1% for the new construction works. In Table 5 are presented Estonian Transport Administration calculations from real cases of construction works. The first construction sites of contractors with this bonus system tend to be less efficient, as it is more like a learning course for them, and then the progress is very evident as contractors understand which properties or actions of them influence the result of the paved layer. Also, they are free to use any methodology they want to ensure the temperature of the asphalt mixture on its way to the site and throughout the paving process (Palmi & Truu, 2023).

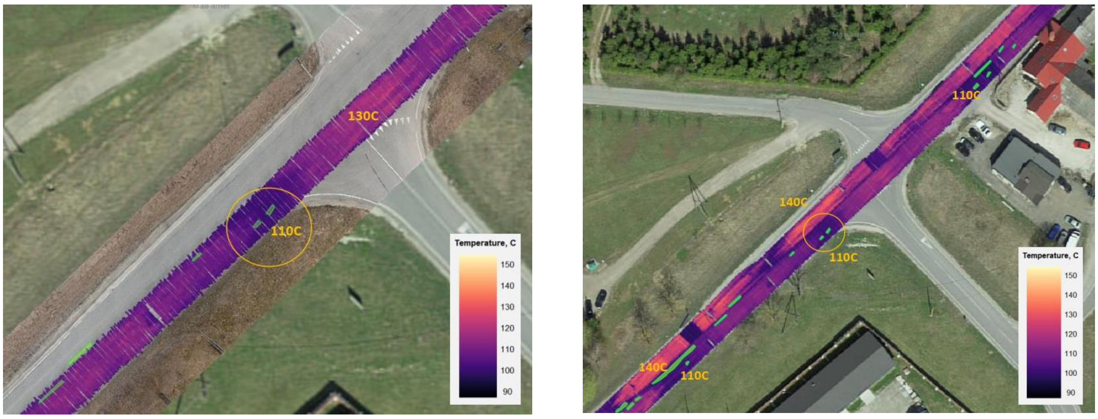
Table 5. Contract prices, bonuses, and estimated savings of different objects according to Estonian Transport Administration *(Palmi & Truu, 2023)*

Case No. 1	1	2	3
No. of lanes	4	2	2
Length of the road section, km	8.8	11.4	10.1
Area of wearing layer, m^2	181 683	98 306	84 000
Price of contract, €	~13 120 000	~3 950 000	~950 000
Bonus, €	88 684.52	64 719.92	47 440.61
Money saved, € (in the period of 20 years)	~600 000	~42 000	~270 000

The focus of this system is on temperature, roughness and compaction, together with requirements for continuous asphalt installation. The temperature has to be recorded in real time and continuously, the registration width has to be not less than 5 m, the registration area has to be in a distance of 2-5 m behind the paver. The measurement interval must be no more than 0.5 m in the longitudinal direction and no more than 0.3 m in the transverse direction. Temperature should be registered with thermal cameras that have registration window of 25ºC-175 ºC (f.e. TGS Pavement technology or the RoadScan of Wirtgen group). All stops (more than 120 s stop) and moments where paver speed is less than 5 m per 2 min are registered and counted. Throughout the paving process it is allowed to make 5 stops in 1000 m distance to still earn a bonus. The bonuses in Estonia’s methodology are paid for two indicators: small number of stops and avoiding risk areas (zones in which the asphalt layer temperature is lower than the average temperature of the 100 m road section and this area must make less than 5% of all paved area) (Raun & Truu, 2021). Another parameter that has to be evaluated is compaction. It is not required to be registered on real-time, but it has to be done in non-destructive methodology, with a ground penetrating radar (GPR). Also, for a smaller value of IRI than 0.6 mm/m in 20 km section, bonus payments are provided. The roughness index has to be evaluated from 2 to 4 weeks after the installation of the asphalt layer. All in all, considering all these requirements and measurements presented in this system, contractors could acquire bonus payment if they met all the conditions for automated registration of quality parameters with several additional requirements for delay of the construction works, fines, and damages, which were registered from the perspective of the contract (Infrastructure Services Development Department, 2017). In the example of Finland testing the bonus system, they got the results of contractors paying attention to provide continuous paver movement, truck trailers coverage in order to maintain higher and equal temperature throughout the whole load in order to reach allowed results for bonus earnings. Furthermore, Finland's methodology has another indicator that is evaluated to obtain the bonus – cold spots area (it should be less than 0.1% of the paving area) (Nevalainen & Pellinen, 2016). Another advantage of this bonus system is that if the contractor uses modern technologies to register these parameters, they could be easily transmitted to the owner of the road in real time so they can follow the asphalt paving process and its quality parameters in real time.

Thermographic homogeneity versus pavement quality comparisons were conducted to understand if these parameters, which are supervised by bonus systems, influence road quality as a result. The results of the study showed that cold spots on the paved asphalt layer registered during the paving process have become defects. In Fig. 23 presented visually registered pavement defects which were compared with thermographic map (see Fig. 24a) in the 80 m section, where temperature differences are clearly visible among those road sections nearby with higher temperatures. These cold spots were tended to appear at equal intervals, which supposes that asphalt trucks changing were ongoing at these sections (see Fig. 24b) (Palmi & Truu, 2023).

Fig. 23. Visually registrated defect of the asphalt pavement



(a) (b)

Fig. 24. Thermographical maps in comparison with pavement defect locations

1.5. Conclusions

1. Compaction is one of the most important processes of asphalt layer installation, due to the impact on the life of the layer. Insufficiently compacted asphalt layer could cause decreased stiffness and strength level, reduced fatigue life, raveling, rutting, and moisture damage. For the quality assurance phase, to determine the degree of compaction, the cores are extracted, and the density is measured in the laboratory from the core. Technologies used for automated compaction registration are currently in the testing and optimisation phase, when several separate data are collected and presented, but generally these data help managers or operators only predict the degree of compaction and optimise the number of passes of rollers through some areas. Intelligent compaction technology is currently in testing phase, and it is the most precise technology for compaction evaluation so far, but the correlation between NDG (Nuclear Density Gauge) and ICMV (Intelligent Compaction measurement values) results are different according to the compaction process phase (breakdown, intermediate, and finish). Some contractors and roller manufacturers are currently widely using and producing these technologies, so in one side these technologies are tested, and scientists are trying to improve technologies and their output results, and in another side, contractors are already using them in everyday construction works.
2. Temperature monitoring at different stages of asphalt layer installation is the second key moment. This includes temperature supervision in trucks, paver bunker, and asphalt layer. Some studies and technologies were presented for these measurements, but they mainly focused on temperature recording behind the paver. Most commonly IR cameras and scanners are used and tested in order to reach accurate data of the temperature in real time and with the possibility to store them in the database for the quality acceptance phase.

Several studies show that IR cameras and scanners are a pretty reliable technology for using them in paving and compaction processes to determine asphalt surface temperature. Several manufacturers are already offering IR technology-based sensors and devices, that can record temperature up to 10 m width behind the paver screed and represent the data in 25x25 cm tiles, where each tile contains up to 16 measuring points, to install them on pavers and get asphalt layer surface temperature data in real time in order to adapt the compaction procedure and the work of roller operators.

3. For automated registration of width, thickness, and cross slope of asphalt layer in real time of the paving process, no studies were conducted. But according to the novelty of the pavers used nowadays in the paving process and the data that paver operators use, these parameters could be extracted from sensors and softwares and determined in the near future, accepted, and licenced for quality control and quality acceptance stages. According to some manufacturers' suggested pavers and their assistance devices, technologies that evaluate weight of the paved asphalt material, the conclusion could be made that at least layer thickness could be determined with the same sensors, also, if the paver could capture width data. So, all geometrical parameters are linked together, and if one of them could be determined, rest of them could be evaluated or calculated.
4. Bonus methodology systems are created in several countries in North Europe to provide quality in asphalt installation processes. The focus of these methodologies nowadays is concentrated on continuous temperature and paving process registration. Furthermore, certain quality parameters must meet at least minimum values compared to the total paved area, not absolute values, in order to receive the bonus. These systems allow contractors to apply for bonuses if they fulfil quality parameters better than minimum requirements. Contractors can get up to 5% of the whole contract fee. The main indicators for the bonuses are the amount of stops of the paver (not more than 5 stops of more than 2 min length at the 1000 m distance), area of the cold spots (not more than 0.1% of the paved area; required only in Finland) and the area of the risk zones (zones in which the asphalt layer temperature is lower than the average temperature of the 100 m road section and that consists not more than 5% of the paved area). The main focus of the system is on temperature registration behind the paver (measured with thermal cameras on real-time), compaction of the asphalt layer (measured with GPR after the asphalt layer installation) and pavement roughness (measured 2-4 weeks after the installation of the asphalt). After tests conducted in Finlad, the results of this bonus system usage showed that contractors try to put maximum effort in order to reach maximum bonus value and as a secondary result, the asphalt layer installation quality increases. According to Estonian Transport Administration estimations, the bonus

system in their country led to smarter, data-driven, and quality-orientated decisions of contractors on the paving site, and all these actions led to longer pavement life, saving natural resources, and minimising waste. All these results require only minor investments to set up such a bonus system, and the result of longer pavement life enables saving the public budget for other investments in the future. An average bonus of 3.5% of the cost of the contract works on a specific road result in 20-50% less expenses in the next 20 years for the repairing works of the same road section.

5. Some measurements are completed and analysed only after the construction works. Road roughness is one of the parameters that contractors must ensure during the asphalt installation process, but it could be measured only after the asphalt paving process. Several different technologies are presented and tested for roughness measurements in order to determine IRI. The most commonly used are high-speed laser profilometers. They show good correlation results in comparison with standard IRI measurements, but wider studies must be conducted in order to ensure correlation at all possible driving speeds, environmental conditions, and traffic situations. In addition, technology of tyre pressure sensors is presented, but the tests carried out showed that the correlation and reliability of the measurement results is low in this testing phase. For road roughness evaluation, the autonomous robot is being tested at the moment, but only indoor, on a smooth and short track, so this system must be tested under real conditions in the future. Also, asphalt layer density is another parameter, that is registered only after the construction works, when the compacted pavement layer cools down. Ground penetrating radar (GPR) and PaveScan technologies are used nowadays to measure asphalt pavement layer density, but they are still compared with extracted cores data in order to fully understand the devices' reliability. Some of the research already shows high correlation of the results and such devices usage could be expanded among the Contractors in the near future and also it could be used as the part of Quality Assurance (QA) phase.
6. The technologies that exist are being developed, and technologies that have space for further improvement in the asphalt layer installation quality parameter registration field are presented in Table 6.

Table 6. Technologies of automated quality parameters registration

Asphalt layer installation phase	Parameter that is registered	Technology	Manufacturer	Current phase of technology developement
Asphalt plant	Temperature of the HMA	-	-	Initial stage of usage
Transportation	HMA temperature in truck trailer	WITOS Paving	Vogele	Currently being tested and used in field construction works.
Transportation	Trucks delivery, waiting and loading times	WITOS Paving	Vogele	Currently being tested and used in field construction works.
Paving	Layer temperature	WITOS Paving	Vogele	Currently being tested and used in field construction works.
Paving	Asphalt layer thickness	WITOS Paving	Vogele	Currently being tested and used in field construction works.
Paving	Asphalt layer width	WITOS Paving	Vogele	Currently being tested and used in field construction works.
Paving	Quantity of material layered	WITOS Paving	Vogele	Currently being tested and used in field construction works.
Paving	Asphalt layer density	WITOS Paving	Vogele	Currently being tested and used in field construction works.
Paving	Distance	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	Tonnage of paved HMA	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	Paved area	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	CO2 emissions of the paver	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	Asphalt layer width	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	Quantity of material layered	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	Asphalt layer density	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	Layer temperature	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	Weather conditions	Pave Assist	Volvo	Currently being tested and used in field construction works.
Paving	Layer temperature and its uniformity	TGS Pavement	Teede Tehnokeskus	Currently being used in Estonia by the Contractors in order to earn bonus payments for the quality registration.
Paving	Layer temperature	Intelligent Construction (IC)	-	Being tested in China
Paving	Paver speed	Intelligent Construction (IC)	-	Being tested in China
Compaction	Roller speed and position	Intelligent Construction (IC)	-	Being tested in China
Compaction	Compaction temperature	Intelligent Construction (IC)	-	Being tested in China
Compaction	Layer temperature	Compaction guidance system	-	Being used by some group of contractors in their rollers. Several case studies are being conducted under a controlled environment.
Compaction	Roller position	Compaction guidance system	-	Being used by some group of contractors in their rollers. Several case studies are being conducted under a controlled environment.
Compaction	ICMV (asphalt layer stiffness)	Intelligent compaction	Bomag, Caterpillar, Hamm, Sakai, TopCon	This technology is in the testing phase for almost 2 decades and is being widely used by contractors at the same time. The result of the case studies varies from bad to good, but further testing is planned to ensure 100% reliability of the IC process results.
Compaction	Roller passes	Intelligent compaction	Bomag, Caterpillar, Hamm, Sakai, TopCon	This technology is in the testing phase for almost 2 decades and is being widely used by contractors at the same time. The result of the case studies varies from bad to good, but further testing is planned to ensure 100% reliability of the IC process results.
Compaction	Asphalt layer temperature	Intelligent compaction	Bomag, Caterpillar, Hamm, Sakai, TopCon	This technology is in the testing phase for almost 2 decades and is being widely used by contractors at the same time. The result of the case studies varies from bad to good, but further testing is planned to ensure 100% reliability of the IC process results.
Compaction	Roller settings (vibration frequencies, amplitudes, speed)	Intelligent compaction	Bomag, Caterpillar, Hamm, Sakai, TopCon	This technology is in the testing phase for almost 2 decades and is being widely used by contractors at the same time. The result of the case studies varies from bad to good, but further testing is planned to ensure 100% reliability of the IC process results.
Compaction	Layer temperature		-	

Asphalt layer installation phase	Parameter that is registered	Technology	Manufacturer	Current phase of technology developement
	Roller position	Compaction Monitoring System (CMS)		Currently it is used as an after-compaction analysis system, but research see a possibility to use it in real-time in the future.
	Roller vibration			
	Layer temperature	Smart Compact; HCQ	Hamm	Currently being tested and used in field construction works.
	Asphalt layer stiffness			
	Weather conditions			
	Layer temperature	Asphalt manager	Bomag	Currently being tested and used in field construction works.
	Asphalt layer stiffness			
	Roller vibration amplitude			
	Layer temperature	IR cameras (mounted on the paver)	-	It is in the final testing phase, because technology is not very complicated, and many contractors already use this technology in their everyday paving works.
	Layer temperature	RoadScan	Vogele	Currently being tested and used in field construction works.
	Weather conditions (wind speed, wind direction, air pressure, humidity)			
	Asphalt layer density	Ground Penetrating Radar (GPR)	-	Currently, it is used more in the quality assurance phase, but in the future, there is the possibility of using this technology at the moment of compaction in real time. Baltrušaitis in 2022 disertation reveals GPR testing results compatibility with conventional testing methods which shows high reliability level in order to ensure stable results in examination of the asphalt layer density
	Asphalt layer density	PaveScan (mounted on the car NDT device)	GSSI	Currently being tested and used by several contractors.
Quality Assurance	Roughness	High-speed laser profilometer	TRRL	Currently being widely tested, but in a semi-controlled environment with limited roughness. Further testing with worse roughness has to be implemented.
	IRI (International Roughness Index)	Dynamic tyre pressure sensor (DTPS)	-	Currently being widely tested, but in a semi-controlled environment with limited roughness. Further testing with worse roughness has to be implemented.
	IRI (International Roughness Index)	Autonomous robot P3-AT	-	Currently in the initial phase of tests in a controlled environment with limited roughness. Further testing with worse roughness and in the outdoors have to be implemented.

2. EXPERIMENTAL INVESTIGATION OF ASPHALT PAVEMENT LAYER PROPERTIES IN COMPARISON BY STANDARD AND AUTOMATED METHODS

2.1. The Subject of Experiment and Methodology

To compare asphalt parameters registered in standard and automated manners, the experimental investigation needed to be coordinated with contractors that have technologies that can register some of the quality parameters of the asphalt layer, and those who have objects in which the asphalt pavement will be paved. With such starting requirements for experiment, a survey was conducted in which all big Contractors of Lithuania were included. After receiving feedback, the Ammann ARX 90 Tandem roller (see Fig. 25) of the Parama company was chosen, which could be connected to special remote program, called QPoint for automated asphalt layer parameters registration. This roller was rented for company Fegda for wearing asphalt layer paving process in national significance highway road A5 Kaunas – Marijampolė – Suvalkai.

Fig. 25. Ammann ARX 90 Tandem roller

The asphalt layer, which was prepared to pave, properties were:

Thickness - 3 cm

Mixture - SMA8S

Length of the paving section - 2.2 km

Total width of the paving section - 11.25 m

Width of the paving section in which experiment was conducted - 3.75 m

General length of the reconstructed road section - 7 km (72 - 79 km)

Number of pavers - 3

Number of rollers - 10

The experiment was agreed between all parties included to be conducted on 20 September 2023. The main focus of this experiment was to compare the data that the QPoint program shows in real time and records with the system for future analysis of the paving works with the data, which are received after the cores are extracted and analysed. In addition, nuclear density gauge (NDG) and infrared thermometer were chosen to be included in the experiment to get more widely available experimental data for comparison.

Fig. 26. Experiment location on the highway road A5 Kaunas-Marijampolė-Suvalkai

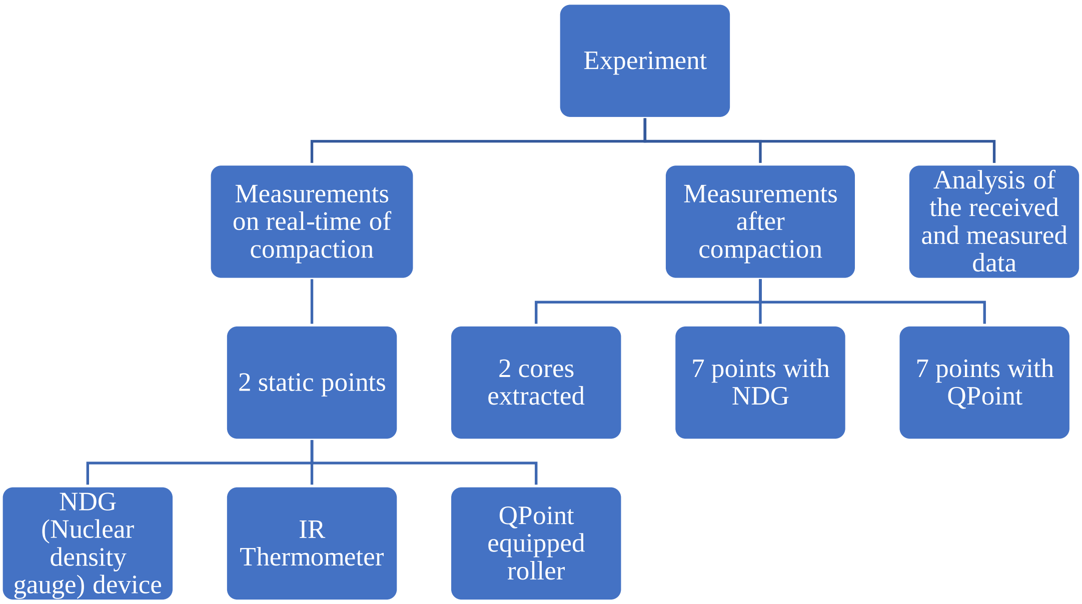


Fig. 27. Experiment scheme

Fig. 28. Reconstructed road section (A5 road 72.00-79.00 km)

Fig. 29. Road section dedicated for the experiment in the A5 road (78.20-78.35 km)

2.2. Asphalt Layer Quality Parameter Measurement

As the tests were conducted with only one roller, the first objective was to determine the location of the asphalt layer paving and compacting processes to be held, to minimise the impact of other rollers for the final compaction values, because the initial compaction parameters could be seen in real time and afterwards via the program, but the core extraction could be held only after the entire asphalt layer paving process. The start location for the tests was chosen at the Sta. 783+50 and the end location at the Sta. 782+00, as the asphalt paving process was organised in the opposite direction of the axis. The roller chosen for the tests was assigned to the safety / paved shoulder lane. Before the tests, a special tablet was mounted in the roller operator cabin (see Fig. 30) and the special module of sensors and devices mounted in the top of the roller. The tablet could work in both embankment and base layers compaction

Fig. 30. Tablet of QPoint program in roller operators' cabin

and asphalt layer compaction processes. It only has to be pre-set before compaction to see which layer it is to be compacted.

Several experimental investigation methodologies were chosen for this object to maximise the amount of data for the report. Firstly, two stable points were selected for parameter analysis after each pass of the roller through that specific point and their comparison with the data of the software afterwards. Second, when analysing the general picture of the object in software, several points were chosen to investigate with NDG and core extraction and compare their results with the software-provided output.

At the first phase of the testing, infrared thermometer registered temperature after each pass of the roller through the specific point (see fig. 31), NDG device registered compaction level, density and temperature of the layer and the QPoint data were extracted from the system afterwards at this specific point, when the exact location by coordinates were determined. The same procedure was repeated at the second point of the asphalt layer, which was compacted with an Amman ARX 90 tandem roller. All the results of these two measurements are provided in Table 7 in the subchapter 2.3. Analysis of the results prepared in the subchapter 2.4.

At the second phase of the testing, the map of the asphalt layer compaction (see fig. 32) was analysed and two spots were chosen for the cores extraction (one, that showed the best result of the compaction [green colour on the map] and one, that showed the worst result [red colour]). The extracted cores are presented in Fig. 35. In addition, several points were chosen only for the NDG analysis, to compare the data presented by the NDG and QPoint software. These points were chosen by different colours on the map to understand how the compaction varies in different compaction zones (see Fig. 32). All the results of these measurements are provided in Table 8 in subchapter 2.3. Analysis of the results prepared in subchapter 2.4.

Fig. 31. Temperature registration after each pass of the roller through a specific point

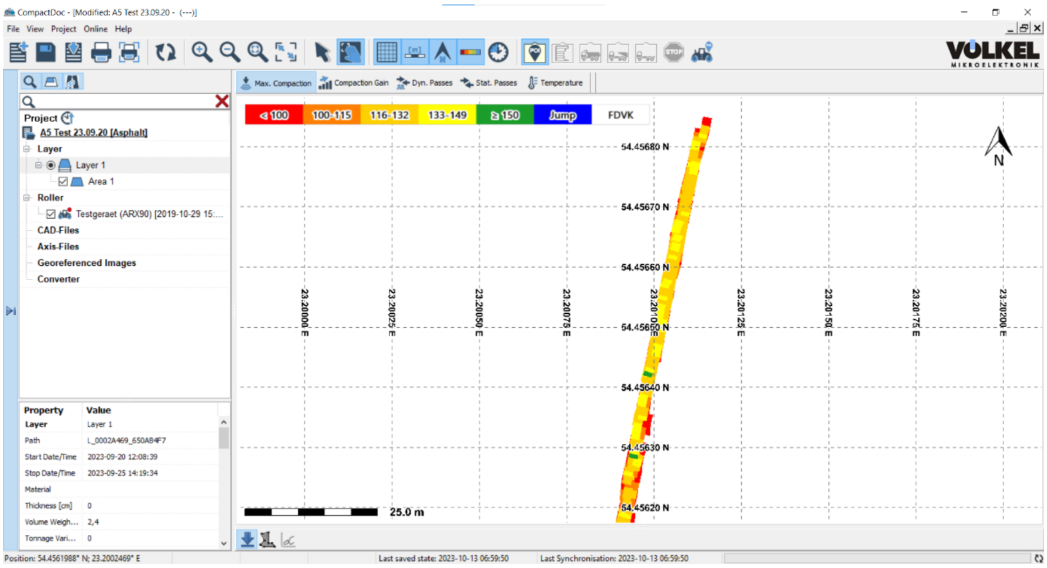


Fig. 32. Compaction map in the QPoint program

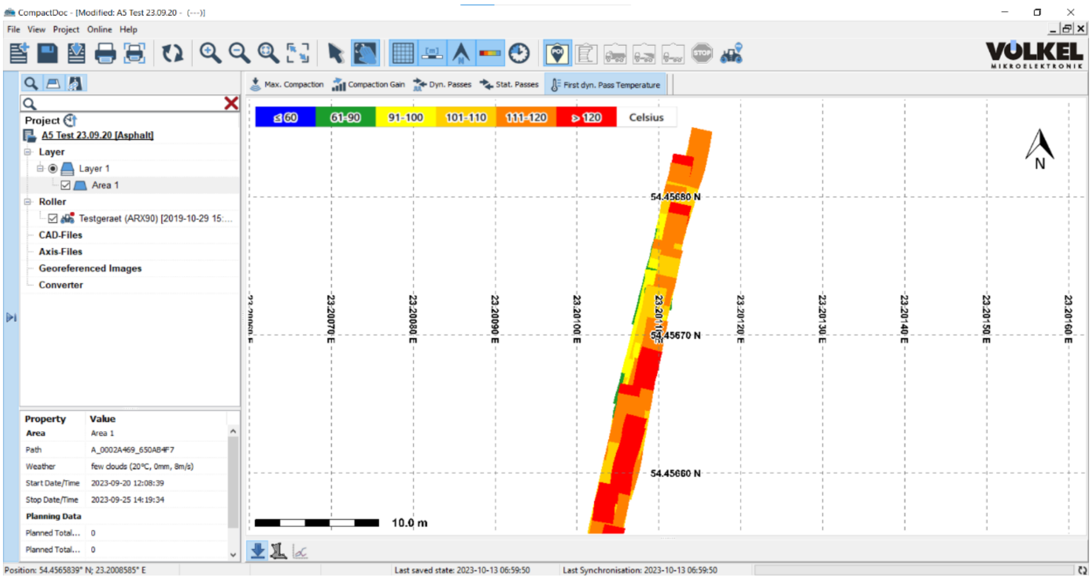


Fig. 33. Temperature distribution map in the QPoint program

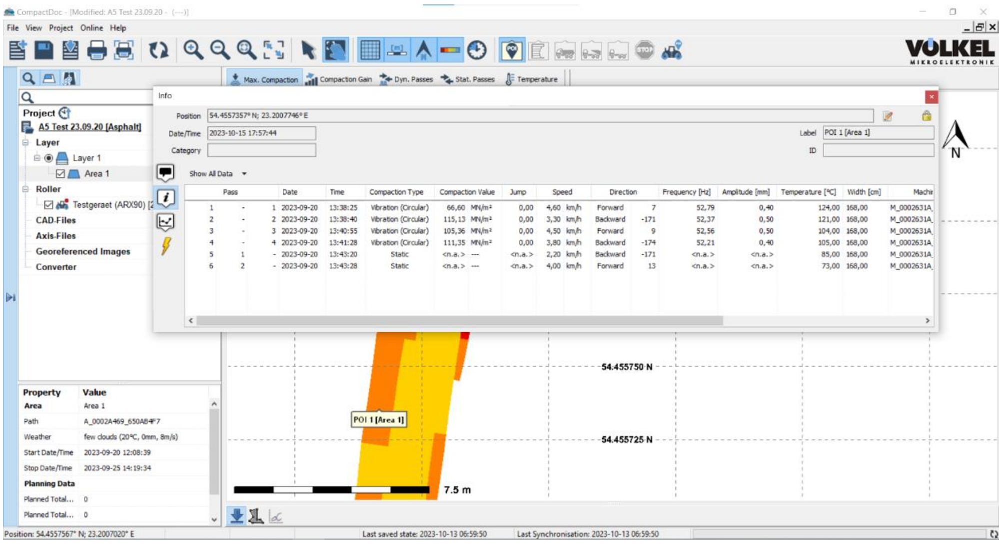


Fig. 34. Specific point quality parameters of each pass in the QPoint program

Also, this CompactDoc application of the whole QPoint program is capable of representing roller in motion afterwards, like a playback function to see the trajectory of the roller movement, which helps to understand and analyse data in various ways and statistical approaches. Dynamic and static passes are represented separately in order not to mix up these data. Basically, this application represents compaction feedback of the roller that passes through a specific point and temperature. These output data, if they are qualified enough after a series of testings in the future, might have a big breakthrough in the quality assurance phase or road construction works, because these are the main parameters that should be registered or recorded during the paving and compaction processes.

Fig. 35. Extracted cores and their visual density, compaction, and air voids

2.3. Results of the Experimental Investigation

The first dataset consists of two points, each with temperature measurements, compaction values, density, air voids content. Registered temperature varies between 111ºC and 134ºC, with an average of 120.42ºC at the first point of measurement and between 88 ºC to 135 ºC, with an average of 111 ºC at the second point of measurement. Compaction values (QPoint) at the first point range from 68.40 to 122.04 MN/m^2, averaging 103.82 MN/m^2, while at the second point range from 96.53 to 130.54 MN/m^2, averaging 115.50 MN/m^2. Density, content of air voids and temperature measured with NDG has only two values, so the statistical analysis would not be efficient for these measurements. Overall, the dataset in the Table 7 provides insights into temperature, compaction, density, and air voids content measured during the paving process and the measurements taken the day after.

Table 7. Asphalt quality parameters at two stacionary points at the moment of compaction

<table>
<tr><th rowspan="2">No. of pass</th><th colspan="3">Temperature, ºC</th><th colspan="2">Compaction</th><th>Density, kg/m^3</th><th>Air voids, %</th></tr>
<tr><th>Infrared thermometer</th><th>NDG</th><th>QPoint</th><th>NDG, %</th><th>QPoint, MN/m^2</th><th>NDG</th><th>NDG</th></tr>
<tr><td colspan="8">1 point (6035725.68, 448175.17)</td></tr>
<tr><td>1</td><td>133</td><td>-</td><td>125</td><td>-</td><td>119.11</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>134</td><td>120</td><td>119</td><td>99.25</td><td>68.40</td><td>2414.77</td><td>0.75</td></tr>
<tr><td>3</td><td>118</td><td>-</td><td>118</td><td>-</td><td>114.02</td><td>-</td><td>-</td></tr>
<tr><td>4</td><td>116</td><td>-</td><td>116</td><td>-</td><td>95.53</td><td>-</td><td>-</td></tr>
<tr><td>5</td><td>116</td><td>111</td><td>119</td><td>99.02</td><td>122.04</td><td>2409.11</td><td>0.98</td></tr>
<tr><td colspan="4">Measured the next day after the paving process</td><td>98.37</td><td>-</td><td>2393.30</td><td>1.63</td></tr>
<tr><td colspan="8">2 point (6035768.40, 448182.11)</td></tr>
<tr><td>1</td><td>-</td><td>-</td><td>112</td><td>-</td><td>110.66</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>135</td><td>-</td><td>116</td><td>-</td><td>113.85</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>115</td><td>-</td><td>99</td><td>-</td><td>96.53</td><td>-</td><td>-</td></tr>
<tr><td>4</td><td>123</td><td>-</td><td>104</td><td>-</td><td>119.45</td><td>-</td><td>-</td></tr>
<tr><td>5</td><td>118</td><td>-</td><td>100</td><td>-</td><td>121.98</td><td>-</td><td>-</td></tr>
<tr><td>6</td><td>-</td><td>-</td><td>88</td><td>-</td><td>130.54</td><td>-</td><td>-</td></tr>
<tr><td colspan="4">Measured the next day after the paving process</td><td>97.52</td><td>-</td><td>2372.56</td><td>2.48</td></tr>
</table>

The second dataset consists of seven points, each with compaction, density and air voids content measurements the day after the construction works. All these measurements are conducted with NDG and extracted core. Additionally, adding the information retrieved from QPoint system, regarding the compaction. Compaction degree values varies between 97.40% and 100.20%, with an average of 98.40%. Compaction parameter (dynamic modulus) registered with QPoint varies from 97.31 to 152.17 MN/m^2, with an average of 127.40 MN/m^2, at the “Max” parameter value at each point. And at the “Last” value, dynamic modulus of a compaction varies from 29.85 to 116.80 MN/m^2, with an average of 8.84 MN/m^2. Air voids content, registered with NDG device, ranges from 0.52% to 2.13%, with an average of 1.72%. As for density, it was measured with NDG device and cores extracted. Results of NDG device varies between 2381.25 and 2420.24 kg/m^3, with an average of 2391.27 kg/m^3. Overall, the dataset in the Table 8 provides insights into compaction, density, and air voids content measured the day after the paving process.

Table 8. Asphalt quality parameters at specific points that were determined after the compaction

No. of measured point	Compaction				Air voids, %		Density, kg/m^3	
	NDG, %	Extracted core, %	QPoint, MN/m^2		NDG	Extracted core	NDG	Extracted core
			Max	Last				
1	99.48	97.40	152.17	115.94	0.52	4.80	2420.24	2280.00
2	98.00	-	151.67	92.47	2.00	-	2384.31	-
3	98.25	-	110.38	29.85	1.75	-	2390.39	-
4	97.87	-	114.26	84.94	2.13	-	2381.25	-
5	97.95	100.20	97.31	72.30	2.05	1.40	2383.17	2358.00
6	98.06	-	140.61	109.55	1.94	-	2385.89	-
7	98.38	-	125.37	116.80	1.62	-	2393.65	-

2.4. Analysis of the Results of the Experimental Investigation

The first statistical evaluation could be prepared for the temperature parameter. When compared infrared thermometer output with QPoint system output (see Table 7), it is visible that only in 3 measurements (from 9) temperature was the same with some deviation (±3 ºC), which consists of only 33% of reliability. The rest of the measurements registered a bigger difference between different registry devices – from 8 to 19 ° C difference. Only in one measurement the temperature according to QPoint was higher than the IR thermometer registered, the remaining 8 cases QPoint showed a lower temperature. The NDG device due to technical issues could only record two measurements, of which one was almost equal to the temperature, registered with the QPoint system (±1 ºC), but they both were significantly lower than those registered with the IR thermometer (- 14-15 ºC). The second measuring point showed slightly lower temperature than the IR thermometer (- 5 ºC) and more lower than the QPoint (- 8 ºC). In the second measuring point, QPoint showed lower values than IR thermometer (by 16-19ºC lower), but the tendency of temperature change is equal. Both of these points temperature registration data is presented in figures 36 and 37. But it is worth to mention that conclusions cannot be prepared from only two measurements with NDG.

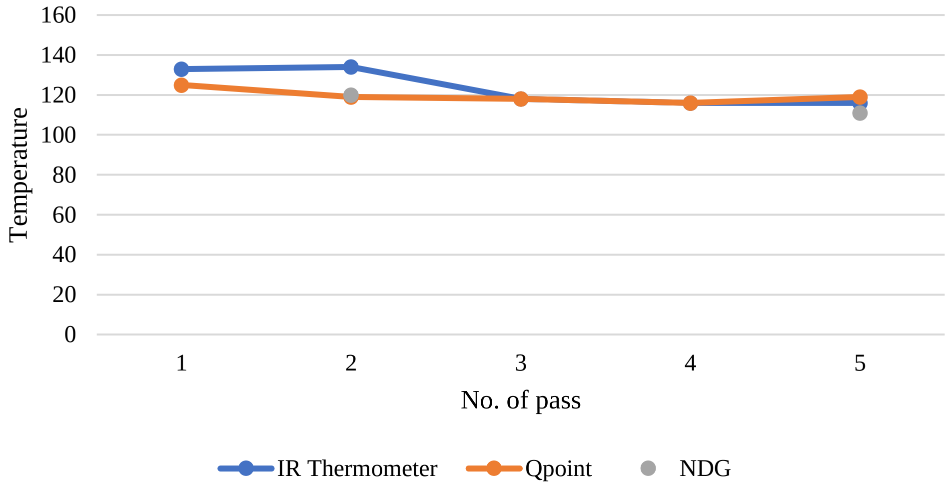


Fig. 36. Temperature measurements at the first inspection point with different devices

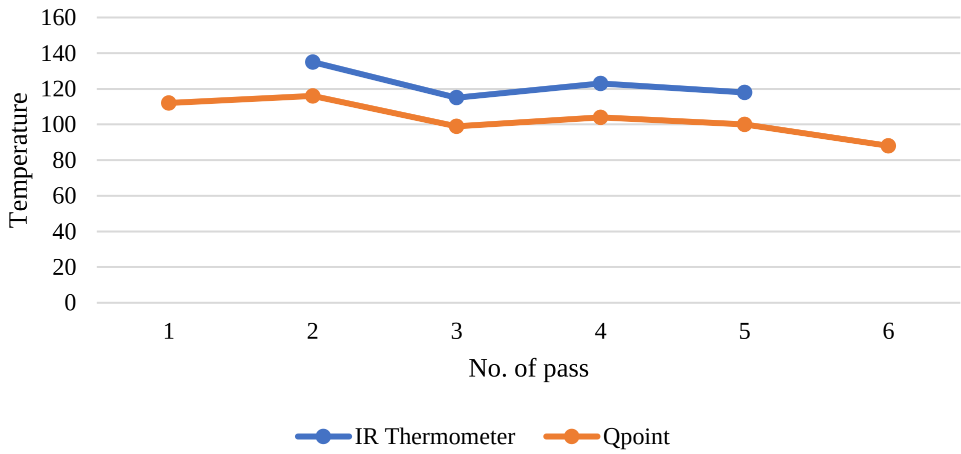


Fig. 37. Temperature measurements at the second inspection point with different devices

Second, the compaction could be evaluated. But insofar as the QPoint system registers only dynamic modulus (or dynamic reaction from the layer) of the compacted layer and the NDG device gives compaction degree value, it is very hard and not efficient to compare this data. Only comparison could be made between 2 and 5 numbers of passes at the first detection point (see Table 7). In both of these passes NDG registered slightly more than 99% compaction degree, but the QPoint system showed drastically different results; dynamic modulus at the fifth pass was almost twice as big as in the second pass. And this increase in dynamic modulus was not consistent throughout the 2-5 passes, because the 3rd pass was almost equal to the 5th already, but the dynamic modulus at the 4th pass was significantly lower than the 3rd and 5th, but not as low as the 2nd one. Another point worth noting is the comparison of the results of the NDG device at the same location at the moment of the paving and the next day after the compaction. The degree of compaction and the density results were slightly lower the next day and the content of the air voids was higher as there is an inverse dependency between density with compaction and the content of the air voids. This measurement means that the NDG device is more reliable with the colder layer and in order to correctly evaluate the data at the moment of compaction, some reduction coefficient could be included.

The same misalignment with the dimensions of QPoint and NDG device results (and extracted cores) have been in a second phase of the experiment. The compaction section of Table 8 shows the registered compaction degree (NDG and core) and the dynamic modulus (QPoint). Only comparison that could be made is proportional when tendencies are compared and evaluated. So, in Tables 9-11 are presented 3 different possible sortings of the data.

Table 9. Sorting by NDG results

No. of measured point	NDG, %	QPoint, MN/m^2	
		Max	Last
4	97.87	114.26	84.94
5	97.95	97.31	72.30
2	98.00	151.67	92.47
6	98.06	140.61	109.55
3	98.25	110.38	29.85
7	98.38	125.37	116.80
1	99.48	152.17	115.94

Table 10. Sorting by Max dynamic modulus value

No. of measured point	NDG, %	QPoint, MN/m^2	
		Max	Last
5	97.95	97.31	72.30
3	98.25	110.38	29.85
4	97.87	114.26	84.94
7	98.38	125.37	116.80
6	98.06	140.61	109.55
2	98.00	151.67	92.47
1	99.48	152.17	115.94

Table 11. Sorting by last pass dynamic modulus value

No. of measured point	NDG, %	QPoint, MN/m^2	
		Max	Last
3	98.25	110.38	29.85
5	97.95	97.31	72.30
4	97.87	114.26	84.94
2	98.00	151.67	92.47
6	98.06	140.61	109.55
1	99.48	152.17	115.94
7	98.38	125.37	116.80

These sortings show that in every possible way, there is no visible connection between all compaction and modulus values. Only two possible conclusions could be made, that by maximum dynamic modulus values and from NDG extracting highest and lowest values, they almost tend to be at the same spot (No. 1 and No. 5 locations). But the last compaction value shows very unreliable values, in comparison with the maximum values, which means, that at the last pass data are not always the values that will be as final.

At the No. 1 and No. 5 (see Table 8) cores were chosen to be extracted to evaluate their data in comparison with the NDG device and QPoint. No. 1 from QPoint was chosen as it showed the highest maximum modulus value and No. 5 as it was the lowest maximum modulus value. The results of the NDG device showed a similar connection, but the extracted core results were drastically inverse, as in No. 1 it registered a lower value (97.40%) than in No. 5

(100.20%). At the same locations as NDG and after core extractions, the air void content and density were compared. The air void content was significantly inverse and in case No. 1 in extracted core it was 9.2 times higher than NDG showed. But in the the No. 5 case in extracted core, it was 0.7 times less than NDG showed. This comparison shows that evaluation of the content of air voids is not efficient and reliable with NDG at the moment, but it is worth to mention that only two measurements were performed, and it is not sufficient amount of data to compare in absolute manner. The same comparisons were carried out with density parameters, and in case No. 1 it was 0.94 times less than registered with the NDG device. In case no. 5, it was only 0.99 times less than registered with the NDG device, which could be treated as minor error, and it could be evaluated as the same value. So, one of the two measurements shows significantly reliable results between NDG and extracted core values, as the other was not that far away with 6% deviation of tolerance.

In comparison to other scientific studies conducted in the same experimental field, it becomes apparent that utilizing only two measuring and comparing points does not provide sufficient data for scientific investigation. In a comparison experiment conducted by Baltrušaitis (2022), one of the non-destructive technologies tested was the NDG (nuclear density gauge), revealing an average correlation to data extracted from cores ranging from 0.472 to 0.557. However, such results indicate only a partial probability of data reliability. Wang et al. (2022) concluded that the correlations demonstrate a strong predictive accuracy between NDG readings and AC mixture density. Various factors, including the components of the mixture and moisture content, can exert a notable influence on the intensity of reflected electromagnetic energy, subsequently impacting NDG measurements. It is crucial to calibrate the system to guarantee accurate predictions using NDG. Kassem et al. (2015) tested CMS (Compaction Monitoring System) and have concluded that it records the entire compaction process for the project, and the data is stored on the computer and database. The software used to save the data also allows for reviewing the entire compaction process. The results obtained from the CMS proved highly beneficial in overseeing the compaction process. Notably, the CMS successfully documented inconsistencies in compaction, such as uneven coverage across the mat, non-uniform temperature, and significant delays in compaction following the placement of mixtures. This system can ensure a consistent compactive effort, thereby promoting uniform density across the mat. Additionally, the researchers validated a proposed method for predicting density. They tested this method in various field projects, and the results demonstrated a strong correlation between the predicted densities and the actual measurements in some specific points. These past scientific experiments have indicated that certain technologies, such as NDG, exhibit notably high correlations in specific cases, particularly when the device undergoes calibration before compaction evaluation. However, there are instances, as observed in the experimental part results of this thesis (despite the comparison being limited to only two measuring points), where the technology demonstrates only partial reliability. Additionally, other researchers have previously tested a different system (CMS) in comparison with the QPoint system evaluated in this thesis. The consensus regarding the software's usability is consistent, highlighting its ease of use, data collection, storage capabilities, and the ability to transfer data as needed. The software facilitates monitoring of the compaction process through features such as timelapse, temperature tracking, and assessment of compaction evenness. Nevertheless, when comparing the systems and their correlations with extracted cores, variations were observed, preventing the drawing of conclusion insights into reliability or correlation.

2.5. Conclusions

1. The experiment was held on 20 September 2023, in the national significance highway road A5 Kaunas-Marijampolė-Suvalkai. The experiment was carried out with the Ammann ARX 90 Tandem roller, QPoint system, which was mounted on the paver, the nuclear density gauge device (NDG) and the infrared thermometer.
2. The experiment was conducted using two separate methodologies. Firstly, two static points were selected and after each pass of the roller measurements with IR thermometer and NDG device (not after each pass due to technical reasons) were held. After the paving and compaction processes were completed, the data from the QPoint system were extracted at these specific points and compared with the data registered at the time of compaction. Second, after the compaction process was finished, the compaction maps in the QPoint system were analysed and two critical points (minimum and maximum compaction values) were selected for the extraction of the cores and another five points were selected only for the registration of NDG device values.
3. The results of the experiment were compared and analysed, and the conclusions could be made only very carefully, because in the experiment a lot of data were with different dimensions, and some technical issues occurred with the NDG device. But regardless of these circumstances, the results showed very small reliability of these data. In some points, the data matches between separate devices and measurements, but these points are the minority (only up to 30%) of the measurements taken. It is worth to mention that there are a lot of errors and deviations in the data that could possibly occur due to not 100% precise location determination at the moment of compaction and in the analysis phase with the QPoint system.

4. All these measurements results depend on the mixture of the asphalt used for the paving. Every mixture has its own dynamic modulus values at the same compaction degree, so in order to precisely compare every automated registration technology, not one asphalt mixture, not one tandem roller, not one core to be extracted has to be chosen for precise analysis.
5. In this experiment, only several points were analysed in order to understand the general behaviour of the automated registration. In the case of this experiment, results showed that blindly choosing several points for measurements does not provide sufficient information for the general analysis of the technologies. It only shows that if only two points were evaluated, the results could vary by 100% in comparison, so at the moment these technologies are not reliable enough to measure only one or two points in the whole road section to ensure the quality of the installed pavement.

3. SURVEY OF SPECIALISTS ABOUT ADVANCED TECHNOLOGIES USED FOR AUTOMATED REGISTRATION OF QUALITATIVE PARAMETERS OF ASPHALT LAYER INSTALLATION

3.1. The Subject of the Survey

To better understand the problems, challenges, benefits, and costs that Lithuanian Contractors face nowadays, when using the automated registration of asphalt quality parameters in the asphalt layer paving process, the survey was chosen to be conducted. In the survey, mainly Contractors or their representative's opinion wanted to be extracted and shared with the responsible authorities in order to show the real situation and common opinion of construction companies about advanced technologies usage. Bonus systems, that are used in other European countries, that gives chance for Contractors to receive back some amount of fee from contract are also included in the survey in order to understand if this system would be attractive for Contractors or not.

3.2. Creation and Conduction of a Survey

The survey consists of 14 questions. Two questions are made to understand, which reason would be the main to use automated technologies for asphalt layer paving in the case where a bonus system exists and does not exist. These questions ask to rank the reasons for using these technologies from 6 to 1 where 6 is the most important reason and 1 is the least important reason. Several questions are prepared for general understanding, if the Contractor uses such technologies, which of them are used, and if they see benefits for asphalt layer paving quality. Then several open questions follow up in order to get wider opinion and approach of the Contractors about benefits, problems, and challenges for both Contractors and Customers, when using such technologies that register automatically paved asphalt layer parameters. Areas for improvement are also asked to be filled if there are any. The following two questions are dedicated to the bonus system, where the aim was to understand if such a system would encourage Contractors to use automated registration technologies or not, and then the amount of bonus fee for return from contract in percentage was requested to fill. The last two questions were aimed to get to know, how much time will take in Lithuania to fully work and rely on automated registration technologies in the asphalt layer paving works and also if the Contractors see in general the advantage of using such technologies for asphalt layers paving processes and for the asphalt layer quality in general. The prepared survey is presented in Appendices, where

Appendix 1 is a survey prepared in Lithuanian (this survey was shared with all the respondents) and Appendix 2 is a survey prepared in English, to fully understand what questions and rankings were created and selected.

The survey was shared with scientific specialists working on roads design, quality assurance, academic and construction works stages, also to obtain their opinion with a scientific approach. Another group of respondents were road construction companies and their separate workers, which specifically work with asphalt paving processes on site. And finally, the rest of surveys were shared with the representatives of Customers and road network owners in Lithuania. All results of completed surveys are presented in 3.3. subchapter.

3.3. Results of a Survey

Untill the last day of survey 16 filled surveys were received from which 8 was construction companies' representatives (from the top steps of the company to the road construction managers, working with asphalt paving teams directly) (further – Contractors), 2 were representatives of customers and road network owners (further – Customers) and the remaining 6 were from scientists or laboratory employees (further – Scientists). This shows that 50% of responses will be influenced by the opinion of construction companies and their employees (see Fig. 38).

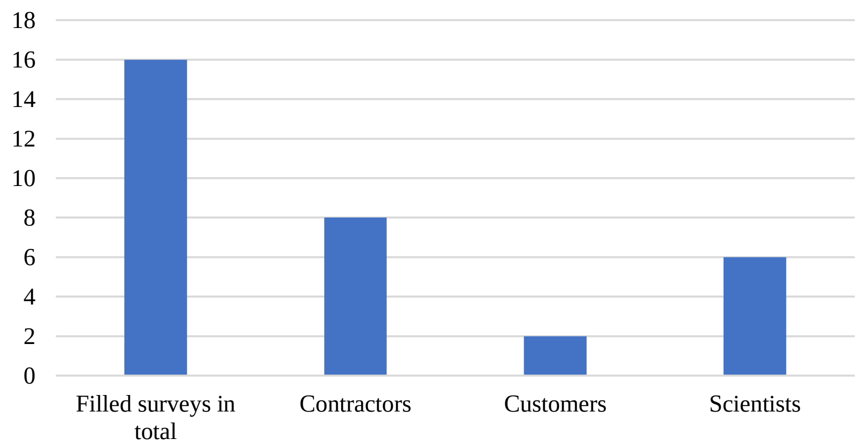


Fig. 38. Distribution of survey respondents occupation

The first two questions in the survey were in the ranking methodology, and all the respondents numbered which sentence they consider the most important (6) and which the least (1), but in the second question a bonus system was added in order to understand whether this variable has influence on the results or not. The first statement was that automated technologies help to reduce the number of extracted cores. This was the least important factor for the Contractors (average 1.8 rank), while for the Customers and for Scientists it was fourth place by ranking (3.0 and 2.7 respectively). With the introduction of the bonus system this statement remained as the least important for Contractors, but also Customers agreed with 1.4 and 1.5 average ranks, respectively. For scientists it remained in the 4th place with average 2.8 rank. In total in both questions, it appeared to be the least important statement with 2.3 and 1.9 average ranks, respectively. There could be intermediate conclusion, with the statement that core extraction reduction is more side effect and benefit than primary goal of automated technologies integration.

The second statement was about the improved quality of road construction and asphalt paving. This statement was second by rank for Contractors (4.5) and first for Customers (5.5) and Scientists (4.8). But in the second question, where bonus system is added as variable, all groups of respondents agreed that this is the most important statement with 4.6, 6.0 and 5.2 ranks, respectively. In total, in both questions it was answered as the most important factor of using automated technologies to improve the quality of roads with asphalt pavements. The average rank of all respondents for this factor increased with the introduction of the bonus system from 4.8 in the first question to 5.0 in the second.

Third statement about reduction of the Customer costs for quality assurance was only 5th by rank for Contractors (2.1 and 1.9 respectively by questions), as they are not interested in cost savings for Customer. But for Customers it was the second most important statement in the first questions (4.5 average rank) and the least important factor in the second question (1.5 rank) as the introduced bonus system would be funded from their budget. Scientist responded more reservedly, because their main interest is not a cost estimation of Contractors or Customers. Their evaluation in the first question was in third place with 3.5 rank, and in the second question it was in second place with 3.7 average rank. In total this statement was ranked in the 4th (with 2.9 rank) and in the 5th (with 2.5 rank) places, with the reduction of average rank by 0.4, when every respondent understands that additional bonus system will cost more for the Customer.

Fourth statement was about reduction of Contractor expenses due to resurfacing of the asphalt layer, that did not reach quality requirements. For the Contractors, it appeared to be the third factor in the first question (4.4 rank) and the first factor in the second question (4.6 rank). This growth or rank itself shows that the bonus system for Contractors seems to be most efficient financially. For the same reason Customer ranking grew from 5th place with 2.5 rank to 3rd place with 4.0 rank. Scientists' replies were also raising from 4th place with 2.7 rank to 3rd place with 3.3 rank. In total, this statement showed an increasing result by 1 place (from 3rd to 2nd) and by 0.6 by average rank (from 3.5 to 4.1). This result shows that introduced bonus system would reduce Contractor expenses due to more qualified asphalt paving processes.

Fifth statement was about reduction of Contractor expenses in a general meaning. For the Contractors itself, it was only fourth place with 3.6 ranking and the same place, but with higher, 4.1 ranking with the bonus system. The most drastic change registered in Customer responses, in the first question the statement was evaluated as the least important with 1.0 rank, but in the second question they evaluated it as the second most important statement with 5.0 rank. So basically, Contractors and Customers say that with bonus system, Contractors could save more expenses than without it. Scientists stayed persistent and, in both questions, showed almost equal results, last, 6th place, with 2.3 and 2.2 rankings, respectively. In total, this statement took fifth place in the first question with 2.8 rank and third place in the second with 3.5 rank.

The last statement was about the benefits of real-time data for Contractors in order to adjust paving process according to received real-time data. In the first question, Contractors raised this statement to the first and most important factor of the usage of automated technologies with a 4.6 rank. In the second question the ranking slightly decreased to 4.4 and 3rd place, but the average ranking shows that it is still one of the most important factors for the Contractors itself. For both, Customers and Scientists, this statement appeared to be the second most important from the list with, equally, 4.5 ranking. In the second question it has dropped to 4th (with 3.0 rank) and to 5th (with 2.3 rank) places respectively. In total, this statement was evaluated as the second important in the list of the first question with the average 4.6 rank and only the fourth important in the second question with the average rank of 3.4. These results show that while there is no bonus system in this market, then every group sees automated technologies one of the benefits, that Contractors could adapt to a real-time data and results. But when the bonus system is applied, then the priorities and the advantages move to other factors, and only the Contractors themselves recognise this as important factor as it was before the bonus system.

Table 12. Average rankings by respondent groups (1 question of the survey)

Total	Contractors	Customers	Scientists	
2.3	1.8	3.0	2.7	a) Reduce the amount of the extracted cores
4.8	4.5	5.5	4.8	b) Increase the quality of road construction/asphalt paving
2.9	2.1	4.5	3.5	c) Reduce the costs incurred by the Customer for quality inspection
3.5	4.4	2.5	2.7	d) Reduce the costs incurred by the Contractor due to the resurfacing of an asphalt layer that does not meet the requirements
2.8	3.6	1.0	2.3	e) Reduce the Contractor's costs in a general sense
4.6	4.6	4.5	4.5	f) Improve the asphalt paving process for the Contractor (real-time data would help to adjust the asphalt paving process in real time)

Table 13. Average rankings by respondent groups (2 question of the survey)

Total	Contractors	Customers	Scientists	
1.9	1.4	1.5	2.8	a) Reduce the amount of the extracted cores
5.0	4.6	6.0	5.2	b) Increase the quality of road construction/asphalt paving
2.5	1.9	1.5	3.7	c) Reduce the costs incurred by the Customer for quality inspection
4.1	4.6	4.0	3.3	d) Reduce the costs incurred by the Contractor due to the resurfacing of an asphalt layer that does not meet the requirements
3.5	4.1	5.0	2.2	e) Reduce the Contractor's costs in a general sense
3.4	4.4	3.0	2.3	f) Improve the asphalt paving process for the Contractor (real-time data would help to adjust the asphalt paving process in real time)

After summing up the general average of rankings of both questions, it is clear that the most important factor of usage of automated technologies remains the increase of the quality of asphalt paving (4.9 rank) and the least important factor remains the decreased necessity of core extraction and reduction of inconvenient potholes in the roads for drivers (2.1 rank). 2nd most important factor is improved asphalt paving processes for Contractors due to on real-time receivable data in order to adjust the paving process (4.0). 3rd place appeared to be reduction of costs for Contractors due to not necessary resurfacing of asphalt pavement if the asphalt layer is paved correctly (3.8rank). 4th place evaluation received the reduction of expenses of the Contractor in general meaning (3.2 rank). And the 5th place evaluation received the reduction of expenses of the Customer, when no need for quality assurance by the conventional methods are longer existing (2.7). All the general data are represented in Table 12 (answers to 1 question), Table 13 (answers to 2 question) and in Fig. 39 (average results of both questions in general).

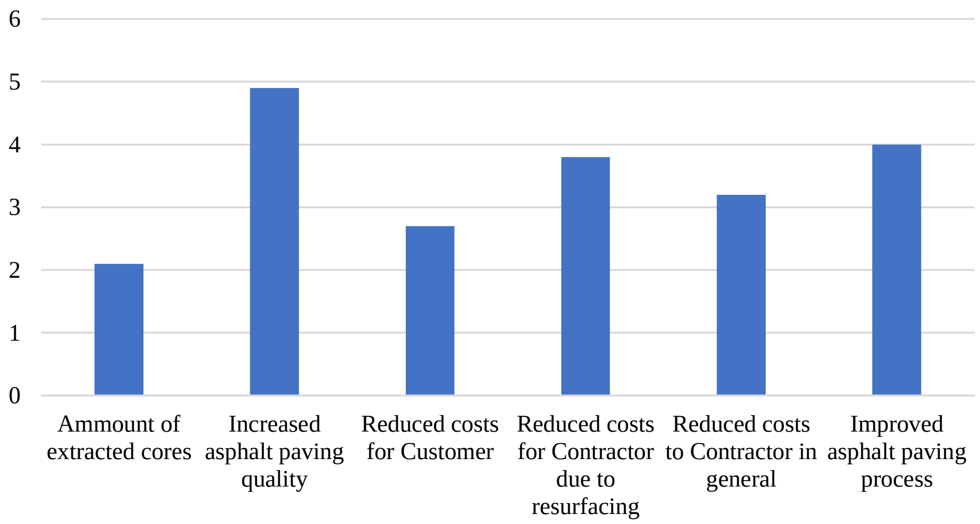


Fig. 39. General rankings of the beneficial factors of the usage of automated technologies in the asphalt layer paving process

Third and fourth questions of a survey were prepared in order to understand how much Contractors use automated technologies for quality parameters registration. 5 respondents from 8 answered that they do not use any specific automated equipment, the other 3 uses some of it, like rollers monitoring, evaluation of compaction, surveillance, air voids content, thickness evaluation, compacted area, temperature, and amount of roller passes through a specific point. Basically, it is only beginning stages of usage of automated technologies, when some Contractors try to understand how it works, how it could be helpful and what advantages and disadvantages these technologies has.

The fifth question focused on understanding the general attitude and general opinion about such technologies. And 100% of the respondents responded that they would use such technologies if it were free and that they see great benefits of using these technologies on the quality of asphalt pavement layers.

From the sixth question, several upcoming questions will be openly answered without choices. Not all respondents decided to answer, but as the benefits for the Contractors, the answers were:

- efficiency of construction works, a more optimal amount of equipment could be used and planned to use for the asphalt paving process (5 responses);
- speed of paving processes and quality assurances (1 response);
- innovation (1 response);
- quality in general meaning (5 responses);
- avoiding possible errors with real-time data; (3 responses)
- reduced amount of extracted cores, which could cause a better lifetime of the pavement, because it is not damaged in initial stages of its usage (2 responses);
- less financial, time, and fuel consumption (2 responses);
- more efficient exchange of the information with the Customer (1 response);
- bonus systems could be used for financial benefits, if they are used in the market (1 response).

From all the answers above it is clearly visible, that efficiency of the construction works and road pavement quality in general are two the most popular answers by respondents, which means, that if the Contractors could make construction works more efficient, the quality will grow simultaneously ar parallel result. The third popular response was that the usage of automated technologies helps to avoid possible errors as the data are perceived in real time. This also causes the asphalt pavement quality to be better and more durable as a final result.

In the seventh question, respondents were asked to fill in all benefits of automated technologies usage they could think of as for Customer. The answers were as follows:

- efficiency of construction works (1 response);
- quality in general meaning (5 responses);
- speed of paving processes and quality assurances (1 response);
- innovation (1 response);
- reduced amount of extracted cores (3 response);
- better pavement lifetime (3 responses);
- reduced costs for Customer for quality assurance, because there will be no need for laboratory investigations (4 responses);
- the status of construction works could be monitored in real-time (3 responses);
- possible fast reaction regarding the construction works decisions, because all the data would be streamed in real-time for the Customer and the Contractor (1 response);
- the quality of the road could be determined and evaluated by 100% area of the pavement and not according to several points converted to cores (2 responses);
- Customers could make payments according to the whole quality map and not according to random point evaluation (1 response);

From the received responses it is visible, that quality of the asphalt pavement is the most important and popular benefit for Customer, according to the respondents. It is the main reason, as the road itself is a Customer ownership and it has to be interested in purchasing the best possible quality of the construction works. Second popular opinion was regarding reduced costs for Customer, when no need for laboratory investigations occur in quality assurance phase of the construction works. In the third row of answers, where every bullet received 3 responses each, stacks up a reduced amount of extracted cores, better lifetime of the pavement in general and the possibility for Customer to monitor the asphalt paving process in real-time by data transfer directly to Customer headquarters.

Moving further from benefits to disadvantages, problems, and challenges of using automated registration technologies, eight questions were focused on disadvantages for Contractors. The answers were as follows:

- high price (having in mind, that every Contractor has several teams working with asphalt paving), which makes the construction works more expensive and reduces the competitiveness of the Contractors (6 responses);
- lack of operator competence, need for more qualified personnel (4 responses);
- missing real-time comparison with conventional evaluation in order to understand the reliability (1 response);

- necessary upgrading, maintenance, and calibration of this equipment, which price could be very high (2 response);
- unavoidable self control in laboratories for Contractors in order to understand the reliability of the data and the paved layer compatibleness to reglamentation (1 response);
- possibility of all Contractors errors to be transferred to Customer in real-time with no possibility to cancel it (1 response);
- lack of Customer efforts to motivate Contractors to use such technologies (1 response);
- restrictions of the reglamentations in order to reach some values (1 response);

The dominant two disadvantages for Contractors were high price, which could lead to reduced competitiveness in the market, and the lack of competence of operators, which could lead to more financial expenses in the form of training and new employees hiring.

In the following question, respondents were asked about the disadvantages for the Customer side of using such technologies in the market. The answers were as follows:

- the need for additional human and IT resources to evaluate the received data (4 responses);
- legal framework, the regulation, and the national legislation are not prepared for this kind of upgrade in construction works (3 responses);
- the construction works would become more expensive (2 responses);
- in the process of procurement and buying of the construction works, some limits may occur, regarding the usage of automated technologies, which could lead to limited competitiveness in the market for some Contractors (1 response);
- the Contractors has to be impartial, and Customers would have to check and ensure that (1 response);
- reliability of automated registration technologies provided data (2 responses);
- the necessity of the bonus system in order to motivate the Contractors to use such technologies (1 response);

The most important factor and disadvantage for Customer was highlighted the need of extra human and program resources in order to efficiently and correctly analyse and evaluate the received data. Secondary problem would be not prepared legal system and all the regulations, which Contractors has to follow in the process of construction works. Another problem would be the rising prices of the construction works, either with a bonus system or with strict requirements in the process of procurement. And the last concern, which was raised by several respondents, is the reliability question of automated technologies, because in the market there are still more questions and doubts than facts and experiments proving the reliability.

The last open question was about areas for improvement for automated technologies, which if would be implemented, then the Contractors would like to use. The answers were as follows:

- the need of autonomy that no human resource is needed to observe the equipment (1 response);
- reduction of the price (1 response);
- the position of the Customer to begin the process with the first motivational steps (2 response);
- the lack of comparison experiments to ensure that data are reliable enough (4 response);

The dominant answer was that automated technologies are not yet showing the reliability of the provided data, but the expanded usage of it would create an expanded database to compare all the conditions with the data. Second answer for improvement, according to the respondents was lack of motivational steps from Customer, for now Contractors are seeking quality in the cheapest possible way, but with the additional motivation, the attitude could be changed.

The eleventh question was focused on the bonus system introduction in the market by Customer and if this variable would influence the Contractors to use more automated technologies or not. The distribution of the answers is presented in Fig. 40. As far as some respondents chose to mark several points, the results are presented in total with the double answers. 62.5% of respondents answered, that they, as Contractors, would definitely use automated technologies if the bonus system would be introduced in Lithuania. 44% of respondents would encourage their companies to make some steps towards usage of such technologies, and only 19% answered that their decision would depend on the returning amount of the bonus system. No responses were received that they would not use such technologies either way, which means that all the respondents would use the technologies with the bonus financial motivation.

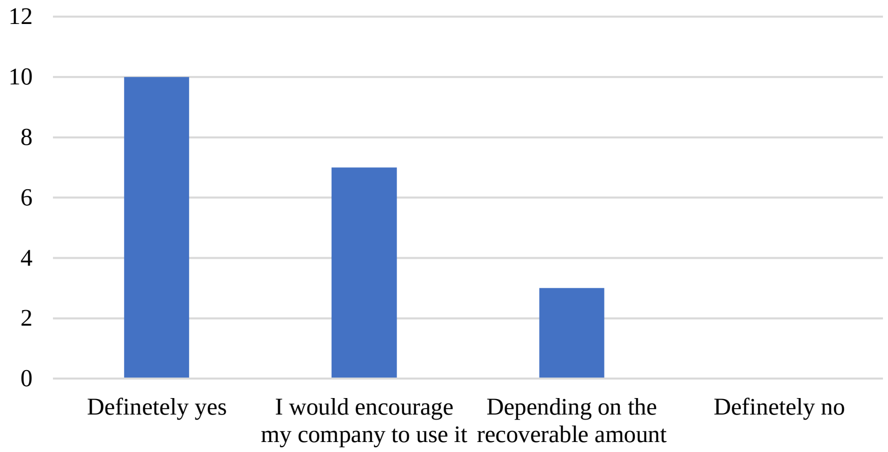


Fig. 40. Distribution of the answers about bonus system introduction influence for Contractors (*Would bonus system in Lithuania encourage You to start using automated technologies?*)

Whereas among Contractors are still some doubts regarding the usage of automated technologies even with the bonus system, another question was prepared in order to understand the desired and appropriate percentage amount of returnable bonus. The distribution of the answers is presented in Fig. 41. 13.5% of the respondents chosen up to 1% of the answers, 33.5% respondents chosen 1-2% of the expression, 20.0% chose 2-3% and 3-4% expressions, and only one respondent (6.5%) chosen more than 4% of the expression would motivate them to use automated technologies in construction works. One of the respondents (6.5%) chosen to openly answer this question and his suggestion was that the percentage expression would depend on the importance of the construction object.

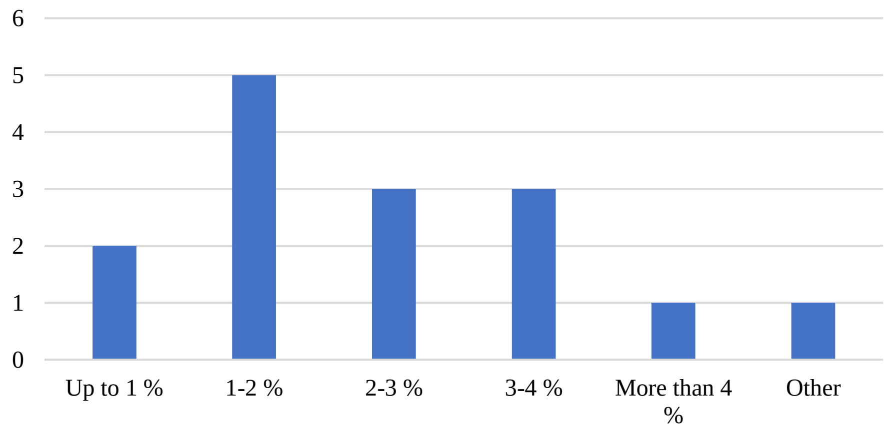


Fig. 41. Distribution of the answers about bonus system percentage expressions *(What percentage expression from the contract price would encourage You to start using automated technologies?)*

In the next question, respondents were asked to fill in how long it will take to fully move to automated registration technologies in the asphalt paving and construction works. The distribution of the answers is presented in Fig. 42. 40% of respondents believe that it could be achieved after 5 years, 33.3% of respondents believe that it could take more than 10 years, 13.3% of respondents think that it could be implemented after more than 1 year. No respondents answered drasticall options, that this implementation could not be done and also that it could be done immediately. Two respondents chose option to openly answer and one of them suggested at least 3-year option and another at least 5-7 years from now. The majority of the respondents – 80% - believe that this full implementation of the automated registration technologies could be done not less than 5 years from now.

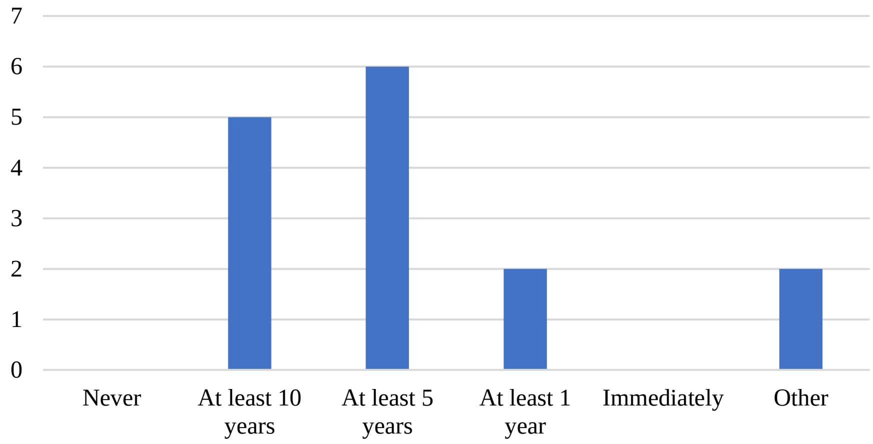


Fig. 42. Distribution of the answers about period till a full implementation of automated registration technologies *(How many years it would take to implement a fully automated quality parameters registration system?)*

The last question asked the respondents to share their opinion in general, how much automated registration technologies would help make the asphalt pavement paving process more efficient and the road quality in general better. The distribution of the answers is presented in Fig. 43. Half of the respondents think that full implementation of the automated registration technologies would contribute to increased road quality either very significantly, or fundamentally change the situation. One respondent (6.25%) chosen the least positive answer,

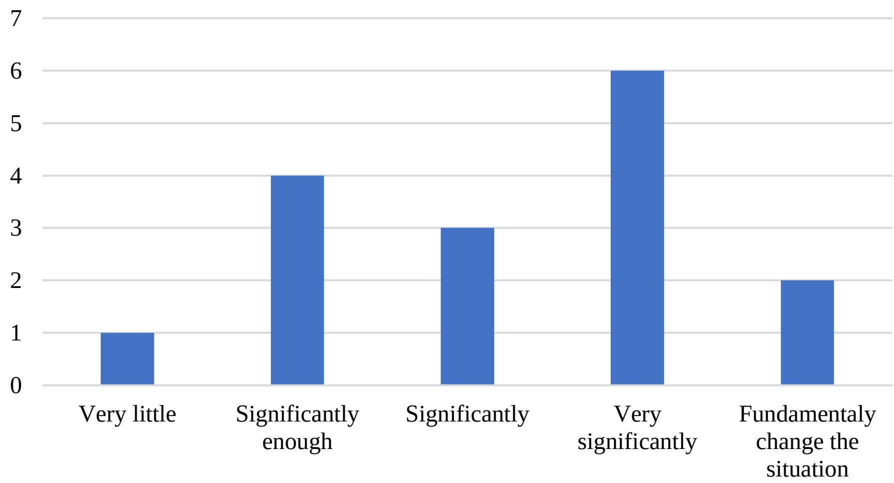


Fig. 43. Distribution of the answers about fully automated registration technologies contribution to asphalt layers and roads *quality (How much fully automated registration of quality parameters of asphalt paving would contribute to asphalt layers and roads quality?*

that these technologies would contribute very little to road quality, 4 respondents (25%) think that it will change the situation significantly enough, 3 respondents (18.75%) believe that it will contribute significantly to improving the situation, 6 respondents (37.5%) answered that such technologies would contribute very significantly to road quality and 2 respondents (12.5%) think that these technologies would fundamentally change the situation of road network quality.

3.4. Conclusions

1. In order to better understand the problems, challenges, benefits and costs, that Contractors in Lithuania faces nowadays, when using the automated registration of asphalt quality parameters in asphalt layer paving process, the survey was conducted. Survey consisted of 14 questions about usage, benefits, problems, and areas for improvement of automated registration technologies, and also several questions about the bonus system introduction, benefits, and desired percentages. Survey was shared to Contractors, Customers and Scientists working in road engineering area. In total, 16 surveys were filled and received. 8 of them were filled by Contractors (50%), 2 – Customers (12.5%) and 6 – Scientists (37.5%).
2. The reduced necessity for core extraction was evaluated as the least important factor, as it is only parallel, but not primary goal. The improved quality of the roads and asphalt paving was the most important factor listed in the questions. Reduction of the costs, that Customers experiences, was evaluated only in fifth place by the respondents, as the majority of them were Contractors. Reduction of costs for Contractors due to resurfacing of the asphalt layer was the third factor in total evaluation of the importance of the automated technologies usage. The 4th place in total evaluation took reduction of Contractor expenses in general meaning. In the Customers answers, there were drasticall changes from the answers, when the bonus system is not introduced and when it is. They believe that it would help Contractors to save a lot of expenses with the bonus payments. The last statement about benefits of the real-time data for Contractors to monitor the real situation, was one of the most important factors for the Contractors and less interesting for Customers and Scientists. This statement dropped from second most important in the first question (without bonus system) to 4th place in the second question (with a bonus system). This drop shows that when there are no additional motivational systems, the automated technologies are helping for Contractors to adapt on real-time with the data on the spot. But when there is an additional bonus system, the priorities already change, and this factor remains lower.

3. As for benefits of the usage of automated technologies for Contractors, most of the respondents answered, that efficiency of the construction works and road pavement quality in general are two the most reasonable benefits, which means, that if the Contractors could make construction works more efficient, the quality will grow simultaneously ar parallel result. As for Customers, increased road quality and reduction of the costs, when no laboratory investigations are needed to be done, were highlighted as the most important benefits. Also, better lifetime of the paved asphalt layer was mentioned as one of the benefits, that could be interesting for the Customers.
4. The main problems for Contractors and Customers were mentioned higher construction prices, possible reduction of competitiveness in the market for Contractors, if special requirements would appear for construction works with automated technologies forced usage, and the lack of competence of operators and the personnel working in the Customer companies, that would do the evaluation of the freshly installed pavement. Also, as one of the problems, not prepared legal system and all the regulations were mentioned, now it is grey zone, with no regulations and evaluation criteria at all.
5. The main areas for improvement by all respondents were selected two. Firstly, reliability questions, as it is not yet determined and solved by the manufacturers and Contractors. Secondly, the lack of motivational steps from Customers in order to encourage Contractors to begin testing and using such technologies to build reliability, database and experience. Survey showed, that only 3 from 8 Contractors use automated technologies in their daily construction works, although 100% of respondents answered, that they would use such technologies if they would be free of charge or in the case of implementation of additional motivational systems for Contractors.
6. 62.5% of respondents answered, that they, as Contractors, would definitely use automated technologies if the bonus system would be introduced in Lithuania. 44% of the respondents would encourage their companies to take some steps towards the usage of such technologies. Most of the respondents answered that the 1-2% bonus system value would be appropriate expression to motivate to use automated technologies. Most of the respondents – 80% - believe that full implementation of automated technologies could be done not than 5 years from now and that it would contribute significantly or fundamentally to the change of asphalt layers and road quality in general.

CONCLUSIONS AND RECOMMENDATIONS

1. According to the literature review, compaction stands out as primary aspect in the installation of the asphalt layer, as it significantly affects the ability of the layer to reach its design life. Inadequate compaction of the asphalt layer can lead to a decrease in stiffness and strength, a shortened fatigue life, and issues such as raveling, rutting, and moisture damage. During the quality assurance phase, the level of compaction is assessed by extracting cores and the density is measured in the laboratory from these cores. Currently, technologies for automated compaction registration are under testing and optimisation.
2. According to the literature review, temperature monitoring during various phases of asphalt layer installation is another most important factor. Several studies and technologies have been introduced for these measurements. They primarily focus on recording temperatures behind the paver. In most cases, Infrared (IR) cameras and scanners are commonly employed and tested to obtain accurate real-time temperature data, which usually is stored in a database and used for the quality acceptance phase. Most commonly infrared (IR) cameras and scanners are registering the temperature in the whole asphalt layer area, directly behind the paver with the width of up to 10 m and could represent the data in 25x25 cm tiles, where each tile could contain up to 16 measuring points.
3. According to the literature review, no studies have been conducted on automated real-time registration of the width, thickness, and cross-slope of the asphalt layer during the paving process. However, considering the innovative nature of the pavers currently used in paving operations and the data utilised by the paver operators, these parameters could potentially be extracted from sensors and software. This could pave the way for their determination in the near future, leading to acceptance and licencing for quality control and quality acceptance stages.
4. According to the literature review, bonus methodology systems, implemented in several North European countries to improve the quality of asphalt installation, focus primarily on continuous temperature and paving process monitoring. Contractors can apply for bonuses by exceeding minimum quality parameters, earning up to 5% of the total contract price. Key indicators include limiting paver stops, minimising the cold spot area, and controlling the area of the risk zone. The system emphasises temperature monitoring behind the paver (real-time thermal camera measurements), asphalt layer compaction (evaluated with GPR post-installation), and pavement roughness (assessed 2-4 weeks after installation). The results from Finland indicate increased contractor efforts to maximise bonuses, resulting in improved quality of asphalt installation. The Estonian Transport Administration estimates

that their bonus system encourages data-driven decisions, leading to longer pavement life, resource conservation, and waste reduction. Minimal investments in the establishment of such systems contribute to the long service life of the pavement, ultimately reducing future public budget expenses for road repairs by 20-50% over 20 years.

5. The experiment, which was conducted on the wearing asphalt layer installation, results were subjected to a cautious comparison and analysis due to varied data dimensions and technical issues with the NDG (Nuclear Density Gauge) device. Despite these challenges, the data exhibited limited reliability. Only a minority of points (up to 30%) demonstrated alignment between separate devices and measurements. It is important to note the presence of numerous errors and deviations in the data, likely stemming from imprecise location determination during compaction and the QPoint system's analysis phase. The reliability of these measurements is dependent on the asphalt mixture used for paving. Each mixture possesses unique dynamic modulus values at the same degree of compaction. For a precise comparison of automated registration technologies, a comprehensive analysis requires selecting not only a specific asphalt mixture, but also a tandem roller and core extraction. Currently, these technologies lack the reliability to ensure pavement quality by measuring only one or two points throughout the road section.
6. A survey was conducted in Lithuania among Contractors, Customers, and Scientists to understand the challenges and benefits of using automated registration for asphalt quality parameters during paving. Respondents ranked statements on the importance of a bonus system. Quality improvement was consistently deemed the most important, while the reduced need for core extraction was least crucial. Contractors prioritised cost reduction for resurfacing, while customers emphasised savings for Contractors. Only 3 out of 8 Contractors use automated technologies daily, despite 100% expressing interest if they were free. Contractors valued efficiency and overall road quality, while Customers focused on road quality and cost reduction due to reduced number of laboratory investigation. The extended lifespan of the asphalt layer was seen as a key benefit. High construction prices, reduced competitiveness, operator competence, and lack of a legal framework were cited as the main problems. The main areas for improvement included addressing reliability concerns and encouraging Customer motivation for technology adoption. 62.5% of Contractors would use automated technologies with a bonus system, and 44% would encourage their companies to adopt them. Most of the respondents confirmed a value of bonus system starting of a 1-2% from the total contract price. About 80% believed that full implementation of automated technologies could occur in five years, significantly impacting road quality.

7. In order to encourage the Contractors in Lithuania to use the automated registration of the asphalt layer quality parameters technologies, the Customers are suggested to step in and begin the legal basis framework adaptation and adjustment in order to accept such technologies usage in road construction works. Also bonus system seemed to be working efficiently in other North Europe counties in order to expand and motivate Contractors to begin the usage of automated registration technologies in order to understand its principles of operation, gain knowledge, experience for operators and to get used to usage and to see its benefits. As later steps, bonus system could be adapted and expanded with the requirements for Contractors and the quality parameters, but the first step has to be only habituation to use such technologies in every asphalt layer paving operation.

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