Case studies & non-highway applications; Success and failure from real practice

Implementation of Low Rolling Resistance Pavements in Denmark

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Abstract

Low rolling resistance pavements have been investigated and optimized during the last six years in Denmark. A durability study was completed by verifying wearing, rutting and cracking resistance. Laboratory investigations were done looking into the asphalt mixtures used for the low rolling resistance pavement. The results have shown that they, if correctly designed and paved, should guarantee a long-lasting lifespan and stable texture, comparable to the conventional mixtures already used on the Danish motorways. The social economic benefit, introduced by the application of this pavement type, relies on the fact that these new pavements should last at least 15 years. In the light of this scenario, the Ministry of Environment has financed a demonstration project focused on paving 50 km on the state road network with the Low rolling resistance asphalt mixture in 2018. Contractors involved in the construction of these pavements were defined by public tendering process. All the paved sections were sampled and controlled following a specific laboratory investigation and paving operations were monitored to assess and verify the quality in the field. Functional characteristics of the finished climate friendly layers were measured and controlled afterwards to verify and validate prediction models. All the different demonstration sections and relative data will be described focusing on the challenges faced by the different contractors; challenges from the optimization of the asphalt mixture at the laboratory to the practical implementation at the asphalt plants and the paving operations themselves.

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1. INTRODUCTION

In 2012, the Danish Road Directorate (DRD) started focusing on low rolling resistance pavements. The first project was named COOEE and the main challenge was to establish a scientific background for developing pavements with low rolling resistance that still satisfy safety standards providing at least 15 years durability [1]. Stone Mastic Asphalt (SMA) was the application of choice because SMA represents the most common surface layer adopted nowadays on Danish roads and consequently contractors have experience with this kind of asphalt. The vision of the project was to optimize the mix design and gradation of a SMA to reduce Fuel Consumption (FC) and CO_2 emission. To reach that target, the research has initially focused on studying the influence of road properties on the rolling resistance (RR) energy losses. RR measurements were performed using the TUG trailer, developed by the technical university of Gdansk, and data were collected over different pavements types and conditions. RR measurement campaign completed in Denmark were also supported by the MIRIAM project and the results confirmed that texture and road smoothness affect RR properties of the pavement [2]. The results could not be used to quantify the relative influence of these road properties on the RR furthermore effect of other relevant variables such tire, temperature and driving speed was not completely exploited [3]. The common outcome of the research was that by reducing texture depth of a pavement it was possible to lower the energy losses generated by the pavement on a rolling tire. The Climate friendly pavement (KVS), also refereed as low rolling resistance pavement, was then designed with the intent to produce a durable layer with low texture depth where friction requirement was still satisfied. Mix design optimization has been faced from 2015 to 2017. Through extensive laboratory characterization, accelerated load testing and small field sections, the main properties of KVS were defined. The gradation of the mixture was optimized starting from a standard SMA8. Texture depth was reduced by increasing the percentage of passing to 2 mm and 5 mm sieve. Hydrated lime was added as an active filler to improve adhesion properties and reduce moisture susceptibility [4]. Different kind of binders and mortars were tested and compared. Satisfactory durability results were obtained using a pre-modified binder and a significant amount of limestone filler [5, 6, 7]. In fact, polymer-modified bitumen improves adhesion and cohesion properties of the AC mixture and guarantees an even distribution of polymers in the mortar increasing the expected service life of the pavement [8, 9, 10].

In 2017, the optimized KVS pavement was paved for the first time on a motorway and, based on the preliminary results, the DRD received a grant from Den Grønne Pulje of approx. 3.0 Mio DKK to take the KVS pavement to a demonstration phase where different contractors were involved. The project objective was to upscale the construction of pavements with low rolling resistance characteristics in order to demonstrate and evaluate benefits and challenges related to this new mix type. Four different test sections were paved by four different contractors. KVS specifications were given by the DRD based on the CE marking EN13108-5. All the produced mixtures and relative binders were tested to evaluate how different mixture ingredients and productions type were impacting the expected KVS properties. Paving operations were monitored and recorded using temperature control. This decision was taken because the experience, gained during the optimization of this material type, has shown that the construction phase has a very strong impact on the functional properties of the pavement. All finished KVS pavements were monitored to verify that the expected requirements and properties were met. All fundamental functional properties such as texture, friction, roughness and noise were measured by the DRD. Rolling Fuel consumption was also studied to verify the final effectiveness of the obtained properties. The present paper summarizes the most significant results collected from the construction of the KVS pavements including properties of the asphalt mixtures, functional characteristics of the finished layer, construction data and expected Fuel Consumption (FC) reductions.

2. CLIMATE FRIENDLY PROJECT PROGRAM DESCRIPTION

Four different contractors were involved in the demonstration project on Climate friendly asphalt. The list of paved test sections is summarized in the table below (Table 1):

Table 1: List of Climete friendly sections paved in 2018

Name	No	Lanes Length [km]	Side	Previous pavement type	Last paved	Paved week
Helsingørmotorvejen	14	1.5	R	50SMA	1993	22
Helsingørmotorvejen	14	1.5	L	80SMA	1993	22
Sydmotorvejen	30	10	R	TBk	2001	42-43
Sydmotorvejen	30	11	L	80AB	2000	41
Østjyske Motorvej	60	4	R	80SMA	1994	31
Skovvejen	119	4	L	60SMA	2005	31

The first three sections were tendered as conventional SMA8 and only in a second phase the contractor adjusted the mixture recipe to the KVS asphalt specifications. The present process could not guarantee proper competition between contractors on the specific product.

Based on these drawbacks, a change in the tendering process was approved. DRD has tendered the last section of Climate Friendly asphalt as a "demonstration project". In this case, it was possible to use the specifications of the EN13108-5 (2016 version). The official name of the mix type was SMA 8 KVS and the following significant requirements were included in the bidding document (Table 2):

Table 2 – list of the significant KVS requirements

Volumetric requirements	
Voids content [Vmin - Vmax]	1.5 - 4.5 %
Voids Filled by Bitumen [VFBmin - VFB max]	80 - 92 %
Voids in Mineral Aggregates [VMAmin]	≥ 18%
Limeston filler [min]	5%*
Hydrated lime	1.5%*
Bitumen	40/100-75
Bitumen Content (aggregate density of 2.65Mg/m3)	7.1%*
Mechanical Requirements	
Indirect Tensile Ratio (water resistance) [ITSRmin]	≥ 80% at 15°C, DS/EN 12697-12
Permanent deformation [WTSAIRmax]	≤ 0,04 mm/103 cycles at 60°C**
Permanent deformation [PRDAIRmax]	≤ 5.0 % at 60°C**
Stiffness Modulus [Smax]	5.000 MPa at 10°C IT-CY
* by mass of the aggregates	
**40 mm thick and compaction ≥ 99 %	

The requirements were defined based on the results of different projects [1,6,7] (COOEE, ROSE, DURAPAV) within which DRD has investigated the durability of low rolling resistance mixtures.
To anonymize the results obtained by the different contractors, the reference to the individual material and section is given by a sub-project number (KLIVE18#xx) where the last two numbers identify the construction and mixture.

3. PRODUCTION QUALITY CONTROL

3.1 Volumetric analysis of the KVS mixtures

Table 3 shows the traditional asphalt data (binder content and densities) and the volumetric proportions of the material which can be calculated from the values. Based on former Danish tradition for open graded asphalt materials, the ration between volume percentage of binder over volume percentage of aggregate is also calculated, as Denmark used to have a minimum value requirement for this ratio in order to avoid lean and moisture sensitive mixes.

Table 3 – KVS data from analysis (binder content, densities and calculated volumetric characteristics)

Characteristic	Unit	KLIVE18#01	KLIVE18#02	KLIVE18#03	KLIVE18#05
Binder content	%	6.4	6.7	6.3	7.1
Aggregate density	Mg/m^3	2.715	2.726	2.916	2.723
Marshall density	Mg/m^3	2.400	2.387	2.536	2.348
Maximum density	Mg/m^3	2.454	2.451	2.610	2.434
Void content	%	2.3	2.7	2.8	3.6
Void in Mineral Aggregate, VMA	%	17.2	18.3	18.6	19.9
Void filled with binder	%	87	85	85	82
Binder-Aggregate ratio (v/v)		0.18	0.191	0.193	0.204

The grading curves of the 4 KVS and a reference SMA8, depicted from the specifications of the asphalt contractors, are shown in Figure 1. All the contractors were capable to fulfil standard KVS specifications. Still, a relevant variability in mix characteristics and finished surface properties were delivered.

Considering the gradation envelope, KLIVE18#01 and #03 were produced with the highest percentage of passing to the 2 mm sieve. Production of KLIVE18#02 was completed adopting a different strategy and % passing 2 mm sieve was kept closer to the lower limit of the envelope. These properties combined with the respective construction qualities gave significant variability of the texture depths. In particular, KLIVEI#03 has shown the lowest Compaction Energy Index (CEI). CEI is calculated, as the area under the curve of percentage maximum density versus gyrations from the 8th gyration until 92 % of maximum density [11]. This value of CEI was used in previous projects [12], but the overall experience with the interpretation of CEI is still limited. In general, CEI values give the perception that KVS mixture has very high self-compacting property given by the chosen mix design. The high percentage of fines adopted to produce a low texture depth have an impact on the relative air voids of the mixture. Also, the percentage of binder enhances the self compactability which can turn into a drawback when compaction temperature is not optimal.

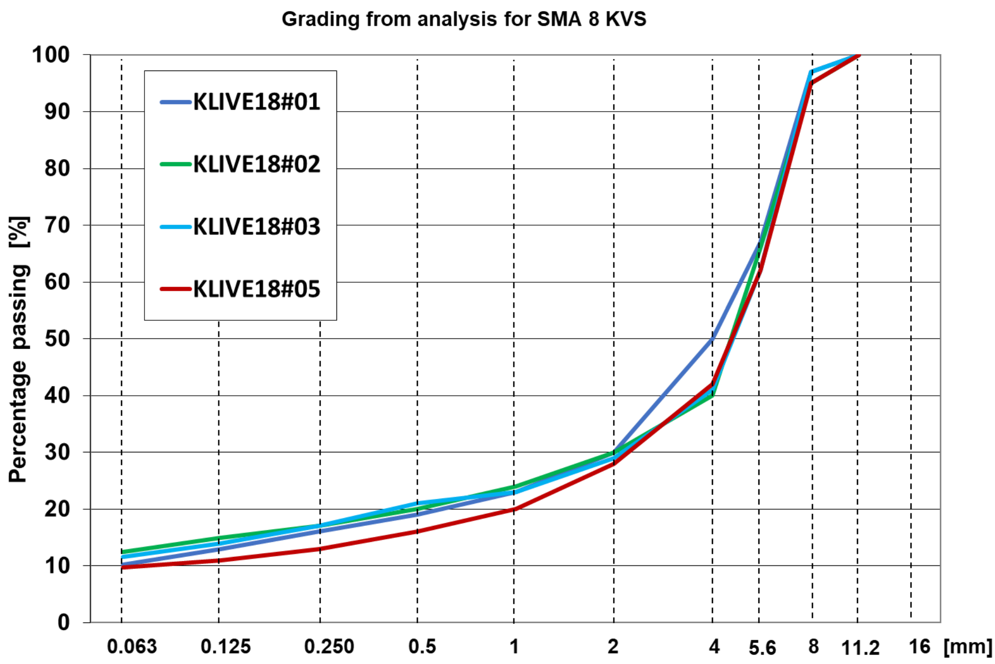


Figure 1 – KVS gradation curves compared to a standard SMA8

Table 4 - Results of gyratory compaction and calculation of Compaction energy Index (CEI)

Gyratory Compaction	Unit	KLIVE18#01	KLIVE18#02	KLIVE18#03	KLIVE18#05
Density after 200 gyrations	Mg/m^3	2.415	2.423	2.588	2.379
Void after 200 gyrations	%	1.56	1.58	0.83	2.28
Compaction Energy Index		5.8	7.7	0.1	19.5

3.2 Mechanical properties of KVS pavements

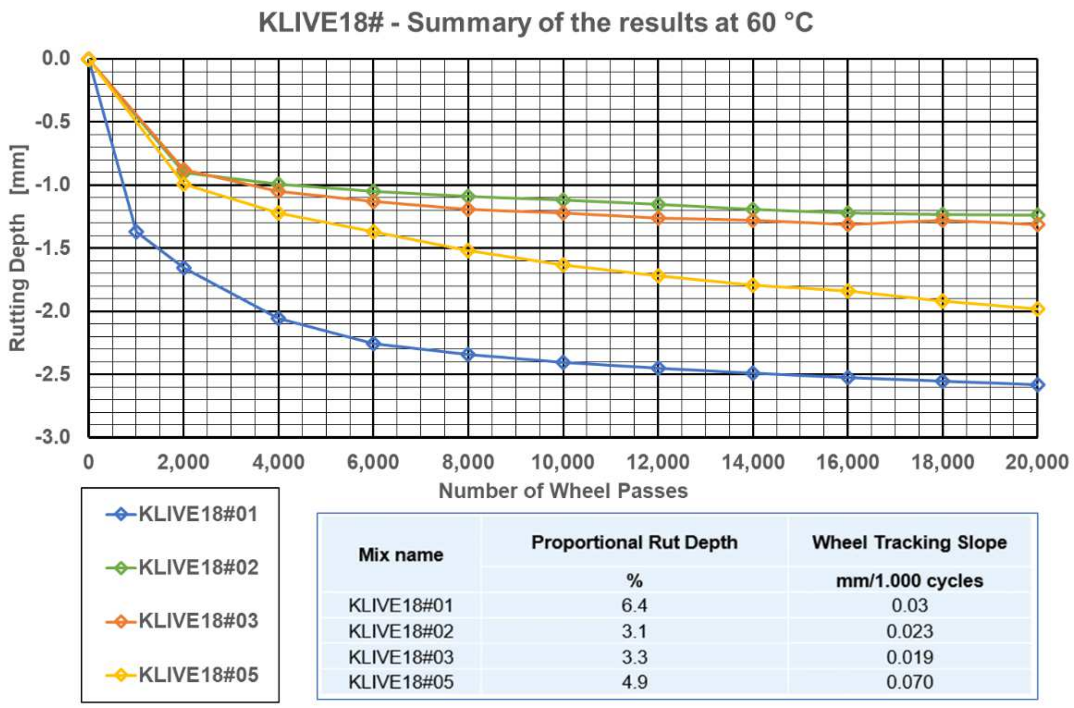
Stiffness modulus and resistance to permanent deformation were evaluated. The first was measured at 10°C and 20°C following the Indirect Tensile Stiffness Modulus (ITSM) tests as described by the DS/EN 12697-26. The standard defines an impulsive load, with rise-time of 124 ms, to achieve the target horizontal deformation of 7±2 µm. The tested specimens were 100 mm in diameter and 40 mm thick and were drilled from 150 mm core produced with the gyratory compactor. For each mixture 6 specimens were tested and a mean value of the ITSM at 10 °C and 20 °C is given together the standard deviation in parenthesis.

A preliminary conclusion on the ISTM stiffness is that the assumption that the desired grading in combination with a 40/100-75 polymer modified bitumen in accordance with DS/EN 14023 does not in itself assure that the ISTM stiffness at 10 °C is below or in the order of magnitude of 5,000 MPa. KLIVE18#02 and KLIVE18#03 have moduli at 10 °C significantly higher than 5,000 MPa.

Table 5 - Measured ITSM modulus (stiffness) at 10 °C and 20 °C. Mean values and relative standard deviation

Characteristic	Unit	KLIVE18#01	KLIVE18#02	KLIVE18#03	KLIVE18#05
Density of samples	Mg/m^3	2.420	2.438	2.587	2.413
ISTM at 10 °C	MPa	5,376 (334)	8,213 (806)	9,655 (641)	4,383 (281)
ISTM at 20 °C	MPa	2,469 (238)	2,569 (137)	3,507 (207)	1,835 (120)
Ratio (20 °C/10 °C)		0.459	0.313	0.363	0.419

Resistance to permanent deformation was studied using the Wheel Tracking Test based on DS/EN 12697-22 + A1:2007. The test involves a set of two pairs of compacted AC samples in a conditioned ambient at 60°C and subjecting them to cyclical loading from a rolling-wheel device. The objective of the test is to measure the depression (in mm) formed on the specimens after a predefined number of cycles, or to record the number of cycles required to achieve a predefined maxi-mum depression level. The results are represented in Figure 2. WTT test results show that two KVS mixtures did not completely met the requirements. Risk of rutting problem is anyway excluded due to many aspects such as: weight x square meter of the paved layer, asphalt sample representativity and very demanding KVS requirements.



Mix name	Proportional Rut Depth	Wheel Tracking Slope
	%	mm/1.000 cycles
KLIVE18#01	6.4	0.03
KLIVE18#02	3.1	0.023
KLIVE18#03	3.3	0.019
KLIVE18#05	4.9	0.070

Figure 2 - summary of the results obtained from wheel tracking test at 60°C

4. CONSTRUCTION QUALIY CONTROL

4.1 Thermal analysis: method description

All the KVS test sections have been monitored during the construction. At each construction site, a paver was equipped with an infrared (IR) thermal camera to monitor the temperature of the newly paved asphalt layer as it left the screed of the paver. Two different but compatible technologies were used to produce the thermal data. These data about paving become interesting when quality and performance of the finished asphalt layer must be guaranteed. Thermal segregation, which can be evaluated using thermal reading, can lead uneven surface properties and premature failure due to a lack of compaction [13]. All the data were processed following a specific algorithm developed for this application [14]. The algorithm was created targeting the identification of those areas which have a low temperature relatively to the average paving temperature. The difference in temperature between two or more adjacent temperature measurements (pixel) was defined as Temperature Gradient (ΔT) and it is a fundamental input of the developed code. Another fundamental input is the Cessation Temperature (C_t) defined as the temperature under which compaction is no longer possible. C_t is also used in the algorithm to trim the newly paved section when is in proximity to an existing pavement and to exclude foreign objects. In the next figure, the processed data by the algorithm are represented as example. The code first trims the raw thermal data:

1) by identifying and removing any part which has temperature lower than C_t; these parts won't be computed as paved area and consequently not used to provide any statistical evaluation of the paved area;

2) from the trimmed data, the code identifies and calculates how much area in the percentage exceeds the critical Temperature Gradient (in relation to any given temperature) and generates a plot (Figure 3).

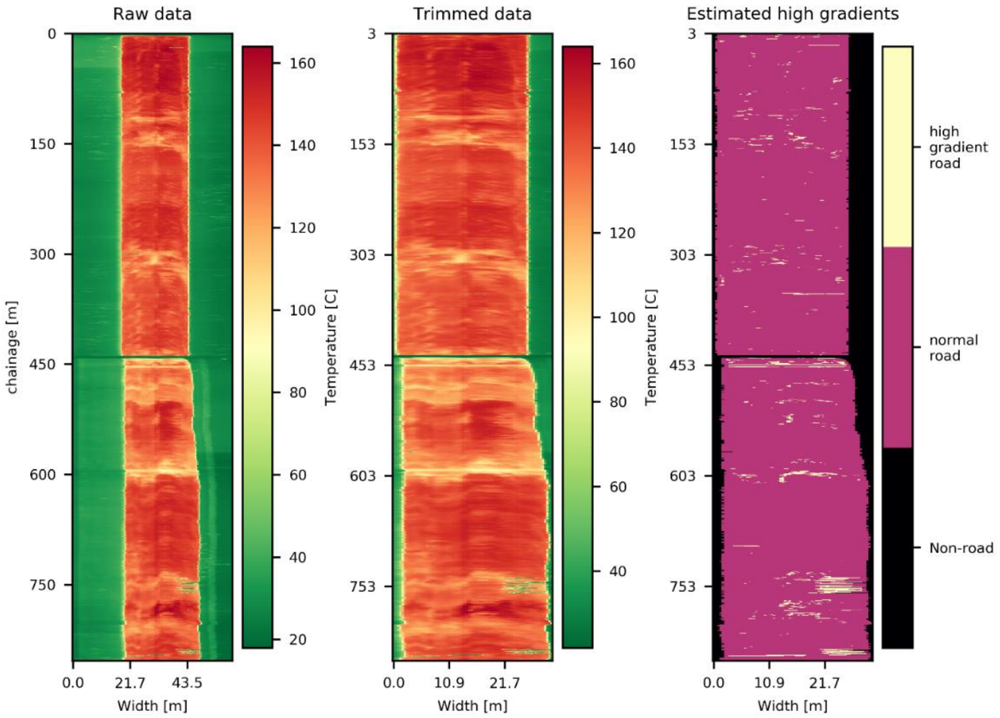


Figure 3: Plot of raw data and plot of trimmed data. Example from a KVS section

4.2 Analysis of the thermal data collected during the construction of the KVS sections

Analysis of the thermal data collected during the paving operations of the KVS sections have been completed focusing on studying variability of the paving temperature. By using the developed algorithm, a percentage of the paved area, which did not fulfil the temperature gradient criteria, was quantified. Different temperature gradients were included in this investigation. All data have been trimmed as described in the algorithm to avoid that foreign objects and pavement joints would affect the statistical analysis. It must be acknowledged that two different technologies were used. It was not possible to compare the two technologies over a standard surface to quantify potential biases related to the two devices.

To better understand the data, relevant information about the paving operations are listed in Table 6.

Table 6 - Differences between the construction sites and thermal devices

Section	Job (day/night)	paver type	feeder (Yes/No)	Thermal Device
KLIVE18#01	night	lane width	No	Type 1
KLIVE18#02	night	lane width	No	Type 2
KLIVE18#03	night	lane width	No	Type 2
KLIVE18#05	day	full width	Yes	Type 2

Figure 4 summarizes the analysis of the paving temperatures and the distribution between 80°C and 180°C considering 10°C intervals. The results show that the section KLIVE18#05, paved during the day and using a feeder, has the most even temperature distribution. 60% of the total area was paved within 140 - 150°C interval and 80% within 130 - 150°C. Based on the produced mix properties, having a big percentage of the paved area within 150 – 160°C increases the risk of drain down problem. KLIVE18#03 is the section which has shown this phenomenon in the field. On the other side, if the temperature is low (between 80 - 120°C) than the mixture cannot be properly compacted, and the surface might result too rough. Temperature analysis shows that this mix type might result difficult to work because of the way it has been thought and demands very even temperature conditions during paving operations. If the mix gets over heated, the thickness of the aggregates coating is reduced increasing the amount of "free binder" which can flow to the surface giving friction problems when voids in the mixture are lower than 1.5% (considering a gyratory sample at 200 gyrations).

Figure 5 shows the percentage of paved area which exceeded the temperature gradient requirement used as input. In this specific case, different gradients have been used as filter in the algorithm and interpolated. These data can be divided into two groups. KLIVE18#01 and KLIVE18#05 have lower percentage of area for most of the investigated temperature gradients when compared to the other construction sites. These data could be used to evaluate thermal segregation by looking into the evolution of the surface properties over the coming years. It is expected that with high gradients, the deterioration rate of the mixture should be high because high is the chance to have segregation in the mixture.

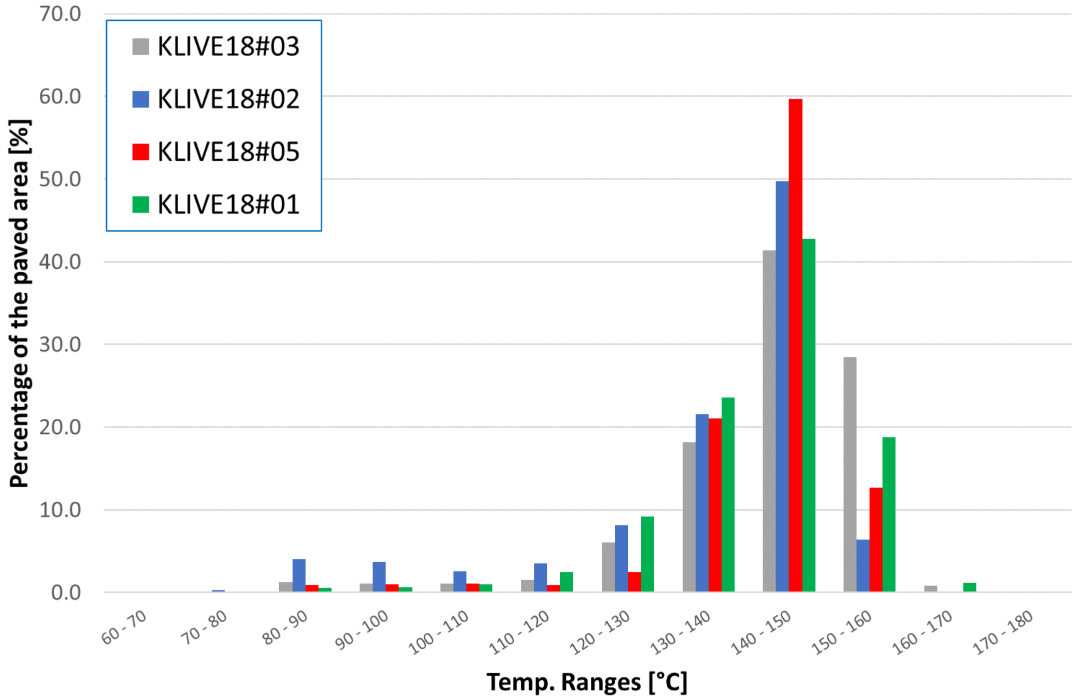


Figure 4 –Temperature distribution of KVS pavements

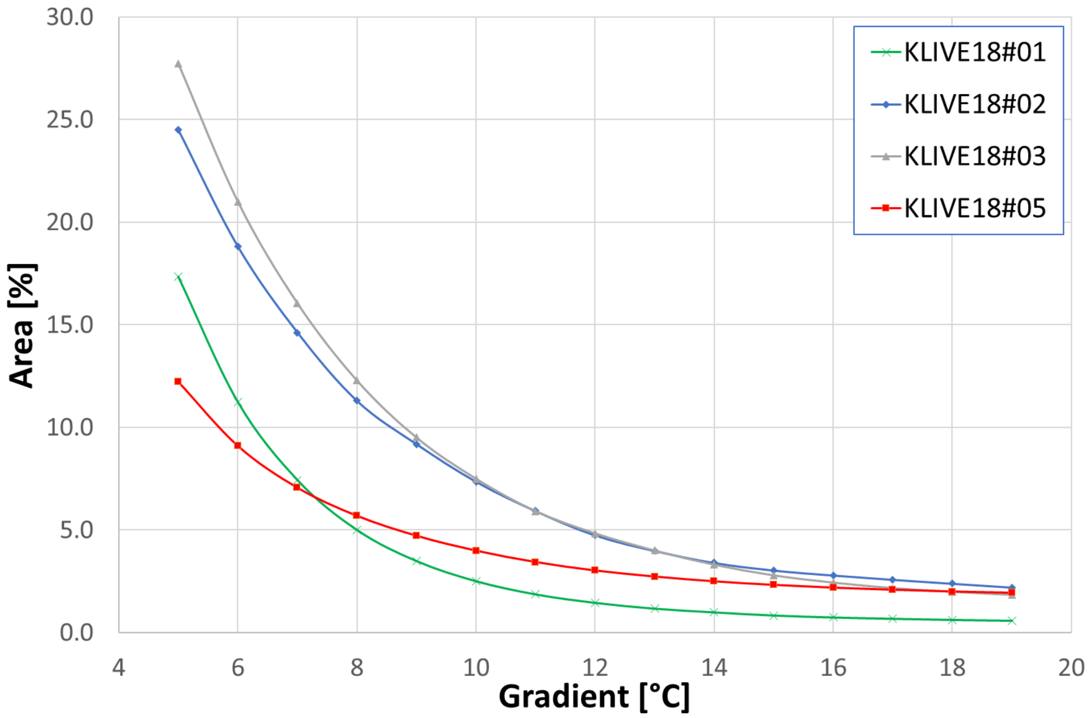


Figure 5 - Temperature gradient and relative percentage of area

5. ANALYSIS OF THE FUNCTIONAL PROPERTIES

The texture of the road surface was measured using a standardized texture measurement system. Every millimeter of travelled distance the height is registered. Data were used to calculate International Roughness Index (IRI) and Mean Profile Depth (MPD).

The friction properties of the test section were monitored using the VIAFRIK following the CEN/TS 15901-14. A fixed slip ratio of 20 % between the measuring wheel and the speed of travel was used. Friction coefficient (Fr) is given as mean friction coefficient at any 100 m stretch. Measurement is done at 60 km/h.

The CPX method was used to perform noise measurements on the Danish test sections with climate friendly, the Standard Reference Tyre (SRTT) was used for all the measurements. The results are corrected to an ambient air temperature of 20 °C (correction factor 0.1 dB/ °C) according to the CPX standard. The measurements have been performed by using the DRD CPX trailer “deciBellA”. When possible, measurements were performed at a speed of 80 km/h.

Figure 6 includes IRI and MPD values measured on KVS pavements. Mean IRI value and relative variability on KLIVE18#01 are not due to the paving operations or milling of the old surface but it has been influenced by the type of structures and constructions on which the new pavement was laid. Average IRI values on KVS pavements are between 0.6 and 0.75 m/km. Considering all the test sections, KVS pavement type has been designed to have an MPD value of approximately 0.5 mm. KLIVE18#01 and #05 are in line with the target while average MPD values on KLIVE#2 and #3 were off. In the case of KLIVE#02, texture was very similar to a standard SMA8 and this might be related to the paving temperature which has not been always optimal during construction. MPD on KLIVE#03 is much lower than what experienced in the other sections and trials, due to both mix design limitations and challenges faced during construction. As documented with the laboratory characterization, voids in the KLIVE#03 mixture were lower than 1.5% on the specimens produced with the gyratory compactor. This property might become critical when combined to temperature variability during production and compaction. In fact, friction requirement (Fr > 0.5 at 60km/h) was not satisfied on KLIVE#03 (Figure 7-Left).

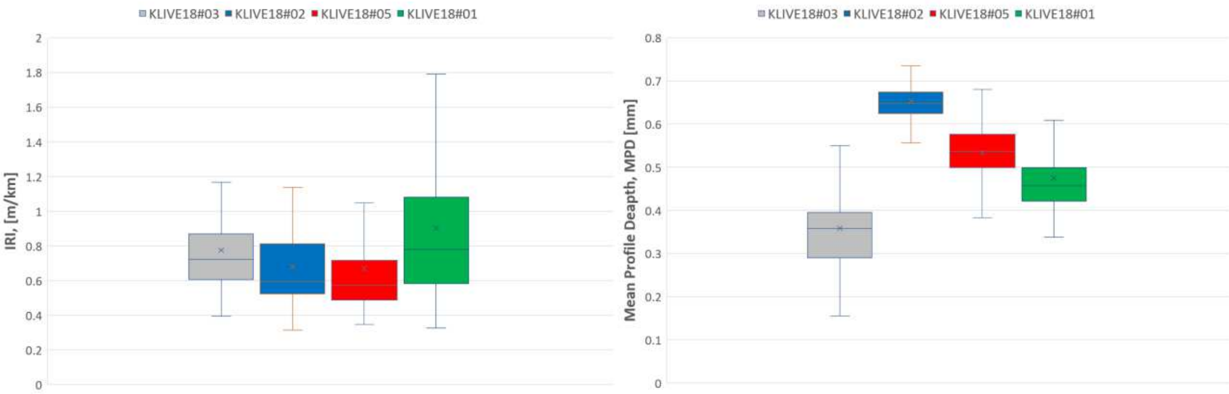


Figure 6-Left. IRI measured on KVS pavements; Right. MPD measured on KVS pavements

From noise point of view (Figure 7-Right), it is possible to highlight that KVS pavements are comparable to standard SMA8. Furthermore, based on the enhanced texture stability [6,12], KVS pavement should have a lower increasing rate of noise emission over time than standard pavements. Noise emissions will be monitored over the coming years to better understand how the enhanced durability of the mixture will reflect on the noise properties.

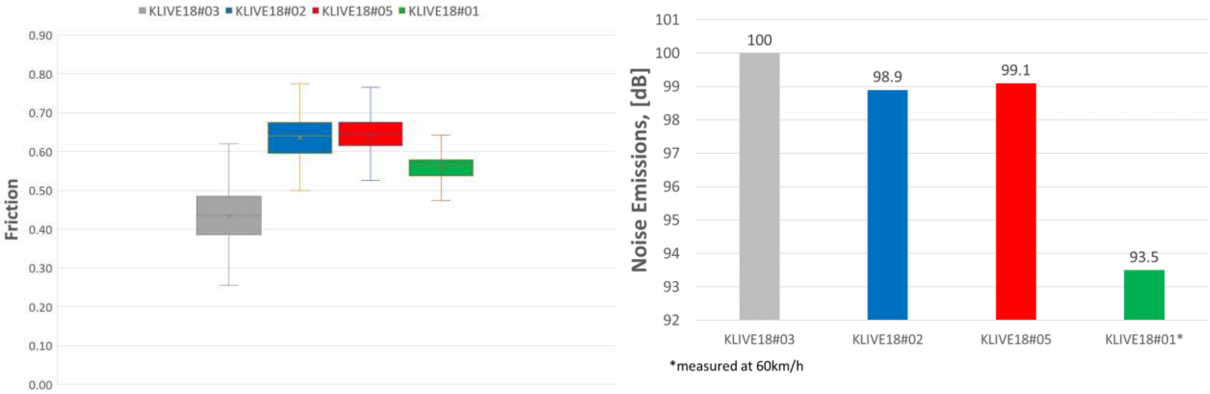


Figure 7-Left. Friction measured on KVS pavements; Right. Noise emissions of the KVS pavement measured (after 34 weeks)

6. FUEL CONSUMPTION MEASUREMENTS

The DRD has contracted a Dutch company “M+P” to measure FC on the KVS and standard sections. The main objective of this investigation was to formulate and define an empirical model to estimate FC in relation to MPD which could be used as support to MIRAVEC model [15]. In fact, FC measurements are affected by many different variables and it is extremely difficult to isolate the effect of the pavement texture when the study includes only few and short sections. For this purpose, FC measurements have been ordered over different types of pavements including most of the KVS sections paved in 2018; KLIVE#01 was not included in the FC measurement campaign due to both amount of traffic normally present at that section and speed limit of 60 km/h. For the measurements, a 2016 Mercedes Vito 119 Bluetech was used. It was fitted with Continental ContiVanContact 200 tires which were set at 3.3 bar at 10°C air temperature. FC was measured from the on-board computer in L/hr. The weight of the vehicle was kept as constant as possible by keeping the tank full and driving with the same number of operators; measurements were completed at the constant speed of 84 km/h and driving with cruise control in highest gear.

A total of 200 km of FC data were collected. All processed data used in this investigation, including texture, were measured from the same vehicle and averaged over 20 meters section length. Texture data and longitudinal profile data point, used in the regression analysis, are averaged over 20 meters section. FC data were corrected by wind, pitch angle and differences in driving speed. Correction models were derived from measurements done in the Netherlands. During the measurements in Denmark, it was noted that the measured wind speeds on some sections had significant higher wind speed than that used for the wind correction model. This introduced some uncertainty in the corrected FC data and for this reason regression analysis on FC data was completed including both wind vectors (crosswind^2, headwind) and MPD. Surface properties of the pavements included in this investigation can be described as follow. IRI data range between 0.3 m/km and 4.2 m/km but 80% of the IRI data are lower than 0.9 m/km. MPD data were between 0.1 mm to 1.4 mm. 90% of the MPDs are between 0.3 and 1.2 mm. IRI was not included in the regression model for two reasons:

- IRI is not a mixture property;
- The range of IRI data set was narrow and, when included in the statistical analysis of the FC data, IRI was found not to be as significant as the MPD.

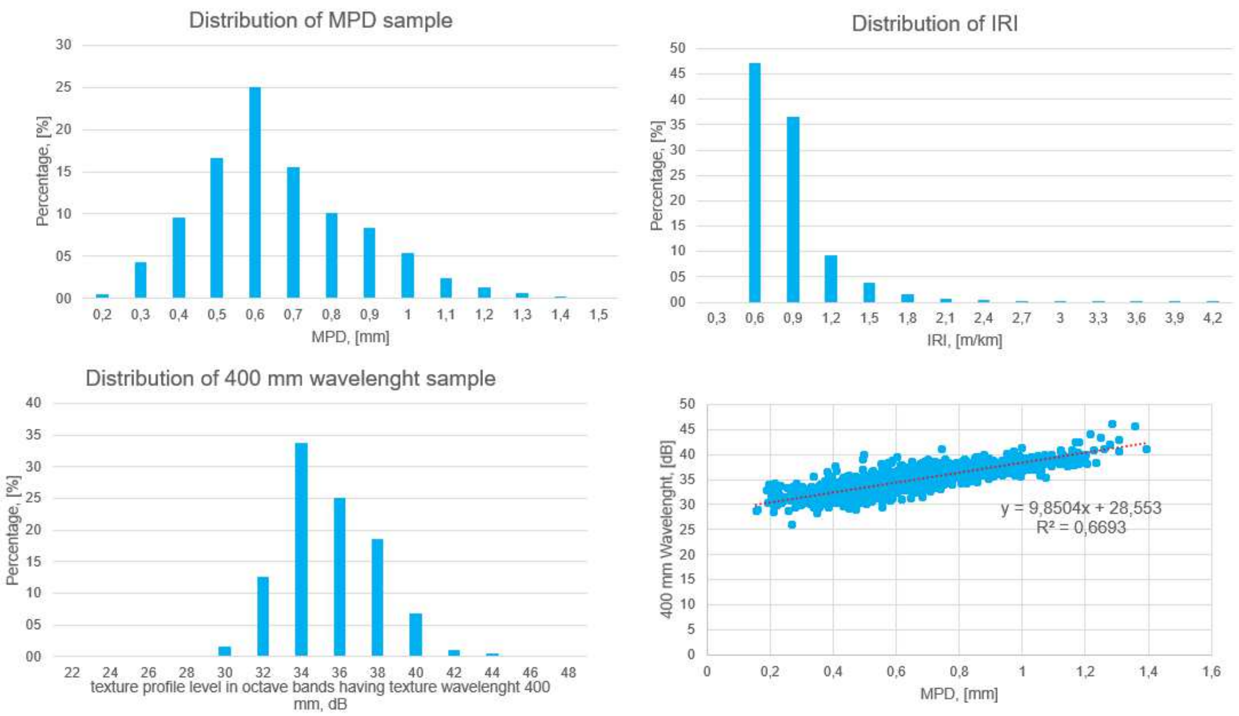


Figure 8 - distribution of MPD, IRI and 400 mm wavelength data set on the pavements where FC measurements was performed

The result of the regression analysis shows that fuel consumption increases with the increase in texture depth (Figure 9). Reliability of the regression model is low (Multiple R = 0.4, R2=0.17) and this is related to the fact that FC is affected by many different variables and surface characteristics have a relatively small impact when compared to others. Furthermore, FC measurement might have as well some variability which could have influenced the robustness of the extracted model.

In general, it is relevant to highlight that the FC reductions calculated using the model, shown in the figure below, does not differ significantly from those developed in MIRAVEC project [17]. Furthermore, assuming a target value of 0.5 mm

MPD, the expected initial CO_2 reductions are approx. 1.0% and 0.4% respectively if compared to standard SMA 11 and SMA8. Due to the enhanced durability and texture stability [6, 16] of the KVS pavements, the CO_2 reductions are expected to increase over the life time up to approx. 2.0% and 1.8% when compared to a SMA11 and SMA8.

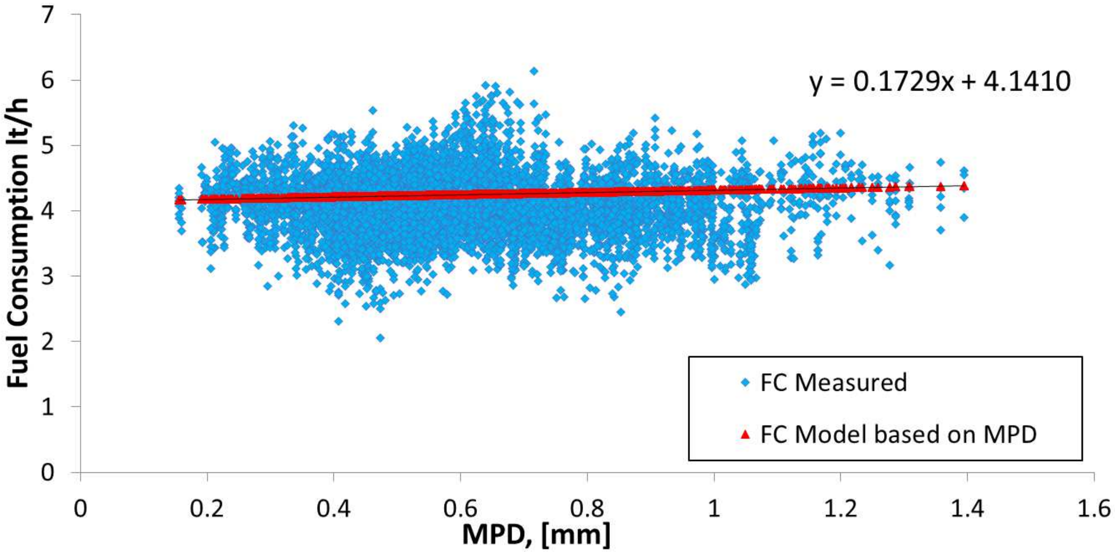


Figure 9 - FC regression model as function of MPD

7. CONCLUSIONS

Four different contractors were involved in the demonstration project about Climate friendly asphalt. Volumetric specifications were fulfilled in all the test sites while it appeared more difficult to comply with given mechanical requirements. Some contractors have found this pavement type difficult to pave compared to standard pavement and to facilitate paving operations and reduce risk, an iterative dialogue between DRD and contractors has leaded towards minor adjustments of the mix specification. This mix design adjustments are not expected to introduce any significant difference in the performances but are expected to facilitate production and paving, reduce risks and improve noise damping effect. All finished KVS pavements were monitored in the field to verify that the expected targets of the surface characteristics were met. All fundamental functional properties such as texture, friction, roughness and noise were measured, and results shown that:

- KVS surface characteristics can be satisfied without compromising safety. The only section where friction limit was not met is the KLIVE#03. In this case, a warning sign (slippery road) was placed in proximity of the section and based on recent measurements, it has been established that the surface of the KVS section on KLIVE#03 will be water blasted to increase texture depth and rise friction properties;
- The difference in MPD between the different contractors are related to difference in production and adopted mix design. In fact, the mix specifications, based on European standards, allow a contractor to define a gradation within a relatively wide envelope;
- Additional information about the field properties of the KVS pavements have been explained using IR camera data. In the specific case of KVS, even temperature conditions are demanded to reduce risks of poor friction. IR data seems also reliable to identify and assess areas which exceeded the temperature gradient requirement;
- using FC measurements, it was possible to extrapolate a linear model that correlates texture depth and FC. Using the developed model, expected FC reductions compared to standard pavements over life time were calculated;
- KVS pavement does offer the possibility to reduce FC compared to standard mixtures. The overall reduction needs to be quantified over the entire life spam of a pavement and it is approximately 1.5% and 1.1% respectively compared to SMA11 and SMA8.

8. ACKNOWLEDGMENTS

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