Climate friendly asphalt

Demonstration project

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Climate friendly asphalt pavement – demonstration project

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Summary and conclusions

The Danish Road Directorate (DRD) received a grant from Den Grønne Pulje of 3.1 Mio DKK to take the recently optimized Climate Friendly Asphalt (KVS) to a demonstration phase. 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.

The project was structured in different Work Packages (WPs):

- WP1 - Identification of sections for energy efficient pavements;
- WP2 - Description of rolling resistance optimised asphalt in tender documents;
- WP3 - Production quality control;
- WP4 - Construction quality control;
- WP5 - Pavements functional characteristics;
- WP6 - Measuring Rolling Resistance and Fuel consumption.

Four different test sections were paved by four different contractors. KVS specifications were given by the DRD based on the European product standard EN13108-5:2016 plus additional features. 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 finished layer.

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 Resistance and Fuel consumption were also measured to verify the final effectiveness of the obtained properties.

In general, the project has shown that KVS asphalt has long lasting texture with reduced Rolling Resistance and fuel consumption properties. Noise reduction of a KVS pavement does not differ significantly from standard SMA8 but it is expected to last longer over time due to the enhanced durability and stability of the texture.

Based on the present demonstration project the following results have been found:

- Expected CO_2 reductions, averaged over a pavement life span of 17 years, are approx. 1.5% and 1.1% respectively compared to standard SMA 11 and SMA8 (Table 18);
- Durability of the KVS pavements is comparable to standard SMA11 (expected life time is 17 years);
- Noise reduction of the KVS is similar to standard SMA8 but it is expected to last longer due to the long-lasting properties; 2 dB noise reduction goal was met only on M30 (Table 14). On the other test sites some challenges were faced during paving.

- Quality of the paving operations have a strong influence on the quality of the finished layer. It is recommended to investigate further the possibility of using thermal analysis during paving.

Most of the contractors have found this pavement type difficult to pave compared to standard pavement types and some minor adjustments have been commonly identified to facilitate paving operations and reduce risks. This mix design adjustments are not expected to introduce any significant differences in the performance but are expected to reduce risks of low friction and improve noise damping effect.

Description of rolling resistance optimised asphalt in tender documents

KVS tendering process and specifications

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

Table 1 - List of Climate friendly sections paved in 2018

Location	Name	No	Lanes Length [km]	Side	From	To	Previous pavement type	Last paved	Contractor	Paved week
Distrikt Øst-danmark	Helsingørmotorvejen	14	1,5	H	400994	410475	50SMA	1993	Munck	22
Distrikt Øst-danmark	Helsingørmotorvejen	14	1,5	V	410000	410520	80SMA	1993	Munck	22
Distrikt Øst-danmark	Sydmotorvejen	30	10	H	1370545	1440020	TBk	2001	NCC	42-43
Distrikt Øst-danmark	Sydmotorvejen	30	11	V	1390495	1430400	80AB	2000	NCC	41
Distrikt Syd-danmark	Østjyske Motorvej	60	4	H	900660	920252	80SMA	1994	YIT	31
Distrikt Øst-danmark	Skovvejen	119	4	V	200700	220373	60SMA	2005	Colas	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 – apart from the grading - were included in the bidding document:

1) *Volumetric requirements*
   - Voids content [Vmin - Vmax]: 1.5% - 4.5%;
   - Voids Filled by Bitumen [VFBmin - VFBmax]: 80 – 92 %;
   - Voids in the Mineral Aggregates [VMAmin]: ≥ 18 %;
   - min 5.0% of limestone filler;
   - 1.5% of Hydrated lime as active filler;
   - Bitumen 40/100-75;
   - Bitumen content 7.1% (based on aggregate density of 2.65 Mg/m^3).

2) *Mechanical requirements*
   - Indirect Tensile Ratio (water resistance) [ITRSmin]: ≥ 80 % at 15° C, DS/EN 12697-12;
   - Permanent deformation [WTSAIRmax]: ≤ 0.04 mm/10^3 cycles at 60°C, 40 mm and

compaction ≥ 99 %, DS/EN 12697-22:2007;
- Permanent deformation [PRDAIRmax]: ≤ 5.0 % at 60°C, 40 mm and compaction ≥ 99 %, DS/EN 12697-22:2007;
- Stiffness Modulus [Smin - Smax]: 1,500 – 5,000 MPa at IT-CY, 10°C and 124 ms; DS/EN 12697-26:2018 Annex C.

The requirements were defined based on the results of different projects (COOEE, COOEE+, ROSE, INNOENERGI, DURAPAV) within which DRD has investigated aspects of the durability of low rolling resistance mixtures.
The drafted tendering document used in the M30 will be revised based on all the collected data from mixtures characterization and functional measurements.
Mix specifications used during the negotiation process and the tendering document from the M30 are included respectively in the Appendix A and B.
After the construction of the different test sections, DRD and the contractors had a very open dialogue where the described specficiations were dicsussed. Both parts have agreed that the present mix design does not give much room for typical production variability. KVS mix design limits and boundries need to be loosened in order to reduce the risks related to construction. Minor changes to the new specifcations should be applied in order to accommodate some of the concerns faced by contractors and experienced in the field. In particular the following changes have been suggested:

- Percentage of passing 2 mm sieve should be 26 – 34 %;
- min. bitumen content from 7.1 to 6.8% (based on aggregate density of 2.65 Mg/m3)
- min. % of limestone filler from 5.0 to 4.5%;
- multiple possibilities about adhesion improving filler:
  a) 1.5% of Hydrated lime
  b) 2.0% of cement
  c) Alternative chemical additive including 1.5 % limestone filler
- Maximum Stiffness Modulus [Smax]: from 5000 to 7.000 MPa at IT-CY, 10°C og 124 ms; DS/EN 12697- 26:2018 Annex C;
- Permanent deformation [WTSAIRmax]: from ≤ 0,04 mm/10^3 to ≤ 0,06 mm/10^3 cycles at 60°C, 40 mm and compaction ≥ 99 %, DS/EN 12697-22:2007.

Production quality control

Material characteristics and fulfilment of requirements

With respect to production quality control and material characteristics, six different asphalt materials, identified in Table 2, were investigated. The materials will be linked to more details about company and project location so in this deliverable the overall reference to the individual materials are their sub-project number, KLIVE18#xx. Other references will only be given in abbreviated form. The rolling resistance optimised version of stone mastic asphalt is in Denmark designated with the abbreviation SMA 8 KVS.

The requirements, which the contractors were faced with, depend on the type of ordering. For the first three demonstration trials, the contractors were asked to fulfil, to the best of their ability, the specifications given in Annex A. Requirements on SMA 8 KVS for tendering the new surface layer om motorway M30 are given in Annex B.

The contractors were asked – preferably before paving – to provide their specification for the mix design including mixture properties such as stiffness modulus and wheel tracking resuts in order to evaluate to which extent the proposed requirements for the mix type SMA 8 KVS were successfully abided. Often the offered characteristics were based on laboratory produced mix since neither time or pre-trials could have allowed for availability of plant produced mix (normally preferred mix type for evaluation of material characteristics in Denmark). In some cases characteristics for rut resistance at 60 °C and stiffness at 10 °C were allowed to be documented after the sections had been paved in order to have access to plant produced mix. The specifiers presumed with some confidence that these characteristics would be "in an acceptable range" if the more traditional composition and volumetric requirements were fulfilled.

Table 2 - Overall designation and main feautures of the asphalt materials

Sub-project number	Material type	Location Road number	Contractor	Type of ordering	Role in project
KLIVE18#01	SMA 8 KVS	M14	Munck Asfalt A/S	Demonstration trial	Candidate material
KLIVE18#02	SMA 8 KVS	Hldv 119	Colas Denmark A/S	Demonstration trial	Candidate material
KLIVE18#03	SMA 8 KVS	M60	YIT A/S	Demonstration trial	Candidate material
KLIVE18#05	SMA 8 KVS	M30	NCC Industry A/S	Tendering process	Candidate material
KLIVE18#06	"SMA 8 KVS"	Systofte	NCC Industry A/S	Functional contract with local community	Pre-trial Variant of KLIVE18#05
KLIVE18#07	SMA 8	M30 ramp	NCC Industry A/S	Tendering process	Reference material

Sampling and delivery control data

In connection with each test section, extensive sampling (~200 kg asphalt and ~5 kg bitumen) was performed for a combination of delivery control and advanced material characterisation. In Table 3 and Table 4, the tests or characteristics are listed with reference to the test standards. This present deliverable concerns only the initial evaluation of fulfilment of the desired target by the individual asphalt contractors.

Table 3 - List of test standards for asphalt materials and additional information on conditions if necessary

Test or characteristica	Standard	Unit
Binder content	DS/EN 12697-1:2006 or DS/EN 12697-39:2012	%
Aggregate density	DS/EN 1097-6:2013	Mg/m³
Marshall density	DS/EN 12697-6:2012	Mg/m³
Marshall compaction temperature	DS/EN 12697-30:2012	
Maximum density	DS/EN 12697-5:2010	Mg/m³
Void content	DS/EN 12697-8:2003	%
Void in Mineral Aggregate		%
Void filled with binder		%
VB/VS ratio		
Gradation	DS/EN 12697-2:2015	
0.063 mm – 11.2 mm sieve		%
Gyratory Compaction	DS/EN 12697-31:2007	
Density after 200 gyrations		Mg/m³
Void after 200 gyrations		%
Compaction Energy Index		
ISTM modulus		
10 °C - mean (std) Marshall compacted sample	DS/EN 12697-26:2012 Annex C	MPa
Density of samples	DS/EN 12697-6:2012	Mg/m³
10 °C - mean (std) [gyratory sample @ 200]	DS/EN 12697-26:2012 Annex C	MPa
20 °C - mean (std) [gyratory sample @ 200]	DS/EN 12697-26:2012 Annex C	MPa
10 °C - mean (std) [plate compacted, cored]	DS/EN 12697-26:2012 Annex F	MPa
20 °C - mean (std) [plate compacted, cored]	DS/EN 12697-26:2012 Annex F	MPa
Wheel Tracking Test at 60 °C	DS/EN 12697-22 + A1:2007	
Wheel Tracking slope, WTS		mm/1000 cycles
Rut Depth, RD		mm
Proportional Rut Depth, PRD		%

The last test method in Table 4 is introduced as a check (primarily on recovered binder) in order to ensure that results for Elastic recovery, Force ductility and rheology are not biased by excessive amount of remaining filler from the extraction of the bituminous binder from the asphalt material.

Table 4 - List of test standards for bitumen and recovered bituminous binder and additional information on conditions if necessary

Test or characteristica	Standard	Unit
Penetration at 25 °C	DS/EN 1426:2015	0.1 x mm
Softening Point Ring & Ball	DS/EN 1427:2015	°C
Elastic Recovery at 10 °C	DS/EN 13398:2017	%
elongation or length at rupture		mm
Force Ductility at 5 °C	DS/EN 13589:2018	J/cm^2
elongation or length at rupture		mm
Rheology - DSR (-10 °C - 100 °C ; 0,01 Hz - 30 Hz)	DS/EN 14770:2012	MPa & °
Rheology - MSCRT (50 °C,. 60 °C & 70 °C)	DS/EN 16659:2015	%
Infrared spectroscopy (KBr, 4000 – 400 cm^{-1})		Absorbans
Ash or remaining filler content	In-house, gravimetric, 430 °C	%

Overview of data availability from the six asphalt materials and their bituminous binders (either original bitumen or recovered binder) is given in Annexes C and D. In the following parts of this deliverable values will be extracted from these tables or from data files which the tables mention as available. At present, the focus primarily will be on the values from the tested materials.

Traditional asphalt data

Table 5 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 ratio 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 5 - Traditional asphalt data from analysis (binder content, densities and calculated volumetric characteristics).

Characteristic	Unit	KLIVE18#01 SMA 8 KVS	KLIVE18#02 SMA 8 KVS	KLIVE18#03 SMA 8 KVS	KLIVE18#05 SMA 8 KVS	KLIVE18#06 SMA 8 KVS	KLIVE18#07 SMA 8 ref.
Binder content	%	6.4	6.7	6.3	7.1	7.2	6.1
Aggregate density	Mg/m^3	2.715	2.726	2.916	2.723	2.720	2.702
Marshall density	Mg/m^3	2.400	2.387	2.536	2.348	2.376	2.320
Maximum density	Mg/m^3	2.454	2.451	2.610	2.434	2.429	2.455
Void content	%	2.3	2.7	2.8	3.6	2.2	5.5
Void in Mineral Aggregate, VMA	%	17.2	18.3	18.6	19.9	18.9	19.4
Void filled with binder	%	87	85	85	82	88	72
Binder-Aggregate ratio (v/v)		0.18	0.191	0.193	0.204	0.205	0.172

Figure 1 shows the grading curves depicted from the specifications of the different asphalt contractor. KLIVE18#01 – KLIVE18#06 are of type SMA 8 KVS, while KLIVE18#07 (with the punctured line) is a standard SMA 8 which is used as a reference in this project. KLIVE18#06 is shown with the same line colour as

KLIVE18#05 but with a dotted line, since KLIVE18#06 was engineered to have the same grading as KLIVE18#05 but with a paving grade 40/60 bitumen.

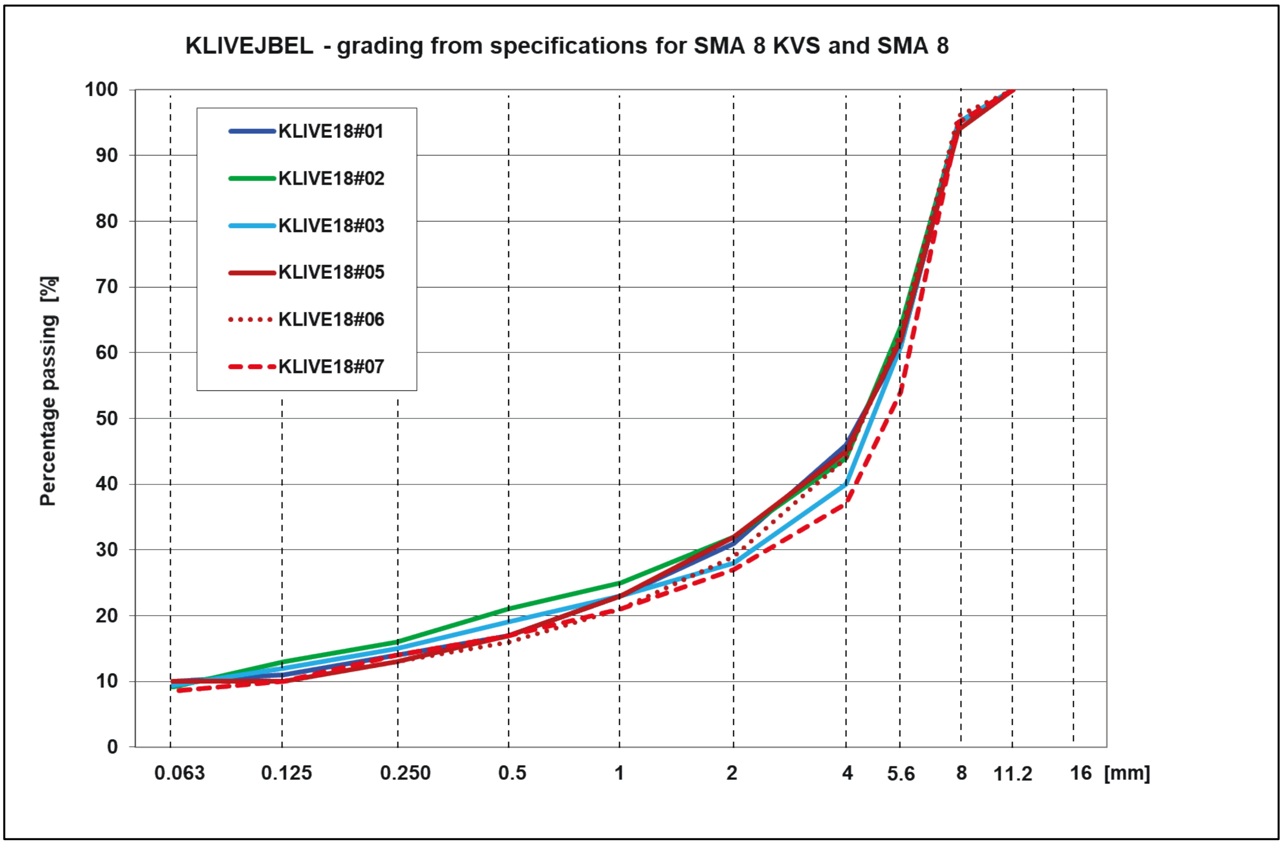


Figure 1 - Grading curves from the asphalt contractors' specifications

Figure 2 shows further details of the grading curves with the difference between the analysed grading curve from the asphalt contractors' grading curve. This graph sums up two elements of potential deviations from the specified value: the first is the standard error by production, sampling and analysis; the second is that some of the contractors were asked to consider minor adjustments of the grading curve in the part below 2 mm just prior to production and paving. The purpose was – based on the experience of the first trial section – to minimise further the risk of having poor friction of the pavement. Since some of the changes happened very late, these were not included in the initial specification which was based on laboratory produced mix. The plant produced asphalt materials were then considered a reliable "reference" because the former specification was based on laboratory produced mix which in Denmark is seen as a secondary level reference for material properties.

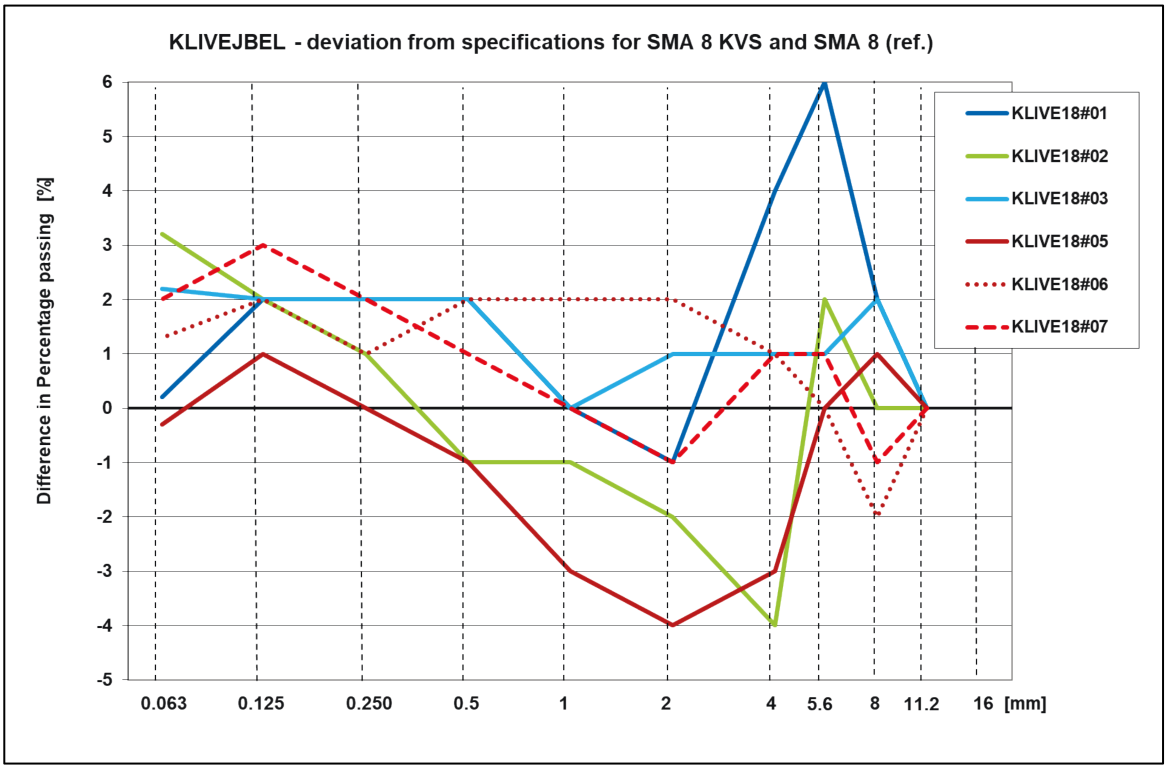


Figure 2 - Difference between the analysed grading curve and the specified grading curve

Figure 3 shows the deviations from the target grading curve of the analysed grading curves of the SMA 8 KVS (as given in Annex A) which has been specified for the asphalt material. Tolerance bands, with respect to single value determination in accordance with DS/EN 13108-21:2016, are included for information. Figure 3 shows that all five SMA 8 KVS grading curves satisfy within the production tolerances the specified mix type as described in Annex A.

Table 6 contains the simple binder data for each of the five SMA 8 KVS and SMA 8 ref. The table includes the analysed data for the original bitumen and the recovered binder. Under each material the contractor's information from the specification/DoP (Declaration of Performance) is added. The softening point Ring & Ball in the DoP for KLIVE18#06 is supposed to represent a neat 40/60 bitumen, while the similar value for the DoP for KLIVE18#07 represents the target value, since this asphalt material contains approx. 14 % of reclaimed asphalt surface layer. For the elastic recovery the value or range of the elongation or length at rupture for three determinations are given.

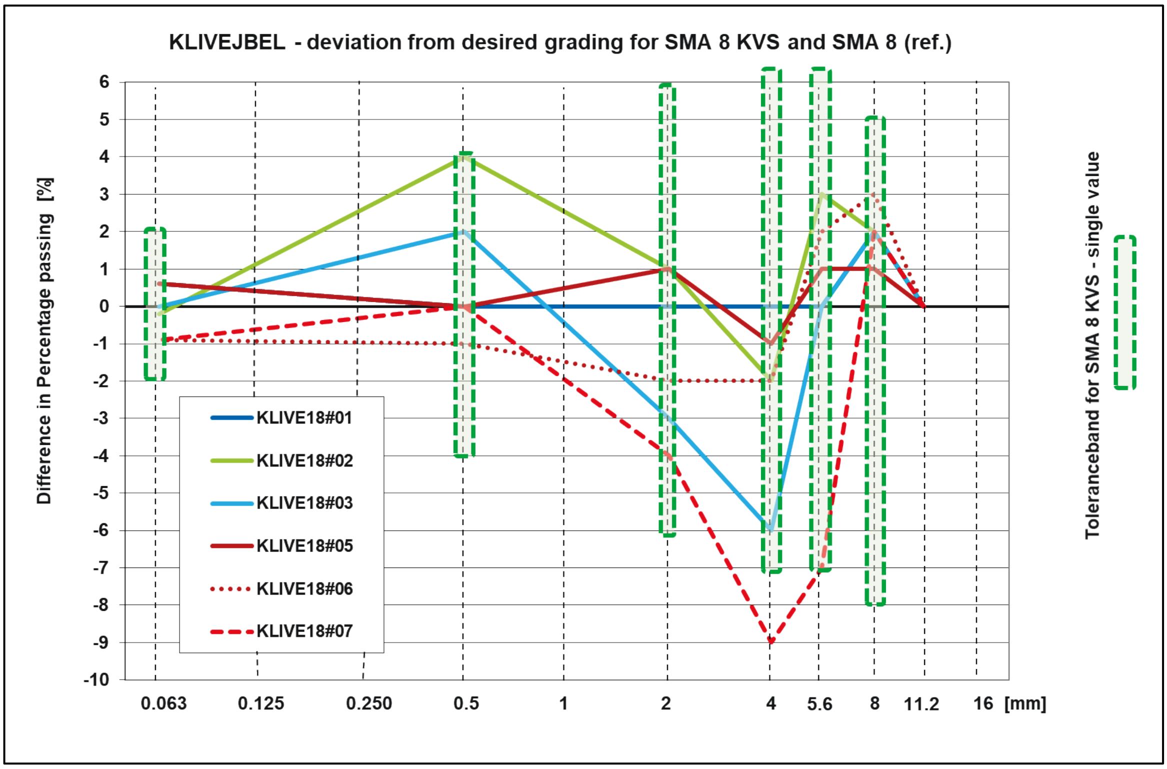


Figure 3 - Deviations from the desired target grading curve of the SMA 8 KVS (see Annex A) and the analysed grading curve including the tolerance bands from DS/EN 13108-21:2016 for single values.

Table 6 - Simple binder data for original bitumen and recovered binder together with contractor's specification.

		KLIVE18#01			KLIVE18#02			KLIVE18#03		
Testmethod	Unit	Original bitumen	Recovered binder	Contractor's specification	Original bitumen	Recovered binder	Contractor's specification	Original bitumen	Recovered binder	Contractor's specification
Penetration at 25 °C	0.1 x mm	81	54	40 - 100	71	47	40 - 100	64	54	40 - 100
Softening Point R&B	°C	70.6	61.2	> 75	76.6	75.2	80.0	76.0	75.4	80
Elastic Recovery at 10 °C	%	86.8	75		77.8	78.3		79.8	76.3	
elongation or length at rupture	mm	200	200		200	200		200	200	

		KLIVE18#05			KLIVE18#06			KLIVE18#07		
Testmethod		Original bitumen	Recovered binder	Contractor's specification	Original bitumen	Recovered binder	Contractor's specification	Original bitumen	Recovered binder	Contractor's specification
Penetration at 25 °C	0.1 x mm	88	59	77	49	38	40/60	49	31	40/60
Softening Point R&B	°C	69.6	64.6	75.0	52.4	54.2	= 55	52.4	58.4	= 55
Elastic Recovery at 10 °C	%	86.1	78.3		5.0	0		7.3	0	
elongation or length at rupture	mm	200	200		50-56	0		0-60	0	

Further assessment of the characteristics of the bituminous binders (among others rheology and ageing) will be dealt with in a future deliverable.

Mechanical properties and characteristics of the asphalt materials

This paragraph includes three items:

- Gyratory compaction;
- Stiffness modulus;
- Wheel Tracking Test (WTT).

Table 7 shows the results of the gyratory compaction with density and voids after 200 gyrations. From the compaction curve, Compaction Energy Index (CEI) is calculated, as the area under the curve of percentage maximum density versus gyrations from the 8th gyration until 92 % of maximum density (Bahia et al.,1998). This value of CEI has been used in previous projects (Pettinari et al. 2017), but the overall experience with the interpretation of CEI is limited. From the values in Table 7, it can be seen that the applicability of CEI on the mortar rich SMA 8 KVS material type might be questionable. Values for SMA 11 has been found in the order of 200 – 400 while a variant of the SMA 8 KVS was close to zero (or with borderline negative single values). In general, these 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 turn into a drawback when compaction temperature is higher than the optimal. This might explain some of the problems obtained during the construction of the section on M60 (KLIVE18#03).

Table 7 - Results of gyratory compaction and calculation of Compaction energy Index (CEI)

Gyratory Compaction	Unit	KLIVE18#01 SMA 8 KVS	KLIVE18#02 SMA 8 KVS	KLIVE18#03 SMA 8 KVS	KLIVE18#05 SMA 8 KVS	KLIVE18#06 SMA 8 KVS	KLIVE18#07 SMA 8
Density after 200 gyrations	Mg/m^3	2.415	2.423	2.588	2.379	2.392	2.424
Void after 200 gyrations	%	1.56	1.58	0.83	2.28	1.53	1.27
Compaction Energy Index		5.8	7.7	0.1	19.5	2.6	43.9

Table 8 contains the measured values of stiffness in accordance with DS/EN 12697-26 Annex C. The mean values of stiffness at 10 °C and 20 °C are given together with the respective standard deviation in parenthesis. The data are also shown in Figure 4. The ratio between the two moduli in Table 8 can be seen as a crude measure for the temperature sensitivity of the material. The asphalt specimens are six cylindrical specimens (approx. 101 mm in diameter and height approx. 40 mm) cored and cut out of three gyratory specimens with a diameter of 150 mm compacted to 200 gyrations. It is important to remember these compaction conditions, when the values eventually shall be compared with data from the asphalt contractor which most likely will measure stiffness on specimen after Marshall compaction (2 x 50 blows).

Table 8 - Measured ITSM modulus (stiffness) at 10 °C and 20 °C on gyratory compacted specimen (200 gyrations). Mean values and standard deviation (in parenthesis).

Characteristic	Unit	KLIVE18#01 SMA 8 KVS	KLIVE18#02 SMA 8 KVS	KLIVE18#03 SMA 8 KVS	KLIVE18#05 SMA 8 KVS	KLIVE18#06 SMA 8 KVS	KLIVE18#07 SMA 8
Density of samples	Mg/m^3	2.420	2.438	2.587	2.413	2.43	2.427
ISTM at 10 °C	MPa	5,376 (334)	8,213 (806)	9,655 (641)	4,383 (281)	9,638 (637)	12,249 (1,269)
ISTM at 20 °C	MPa	2,469 (238)	2,569 (137)	3,507 (207)	1,835 (120)	4,055 (507)	5,903 (809)
Ratio (20 °C/10 °C)		0.459	0.313	0.363	0.419	0.421	0.482

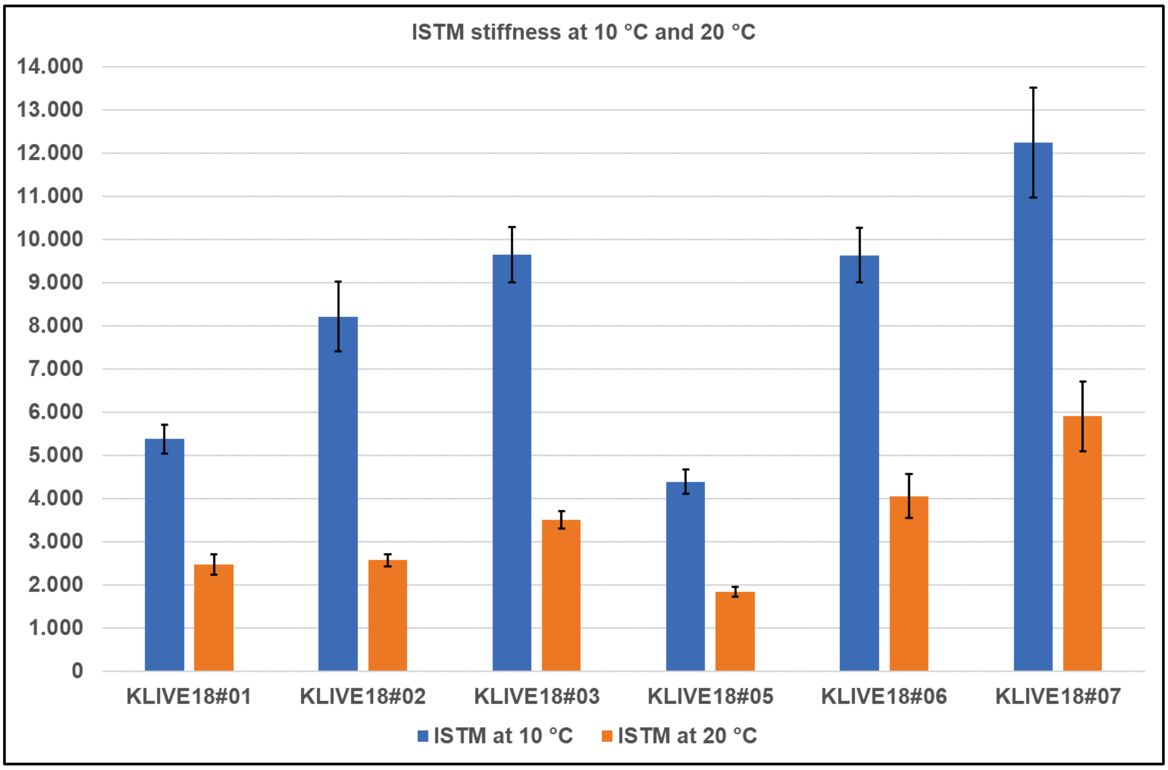


Figure 4 - Indirect Tensile Stiffness Modulus at 10 °C and 20 °C

A preliminary conclusion on the ISTM stiffness is that combining the desired grading curve and a 40/100-75 polymer modified bitumen, in accordance with DS/EN 14023, does not automatically 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 significant higher than 5,000 MPa. Based on these results, DRD has decided to raise the Smax limit from 5,000 MPa to 7,500 MPa. On the other side, some contractors must consider to apply small changes to their KVS mix design.

The procedure for WTT follows 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 pre-defined number of cycles, or to record the number of cycles required to achieve a predefined maximum depression level. The results are represented in Figure 5.

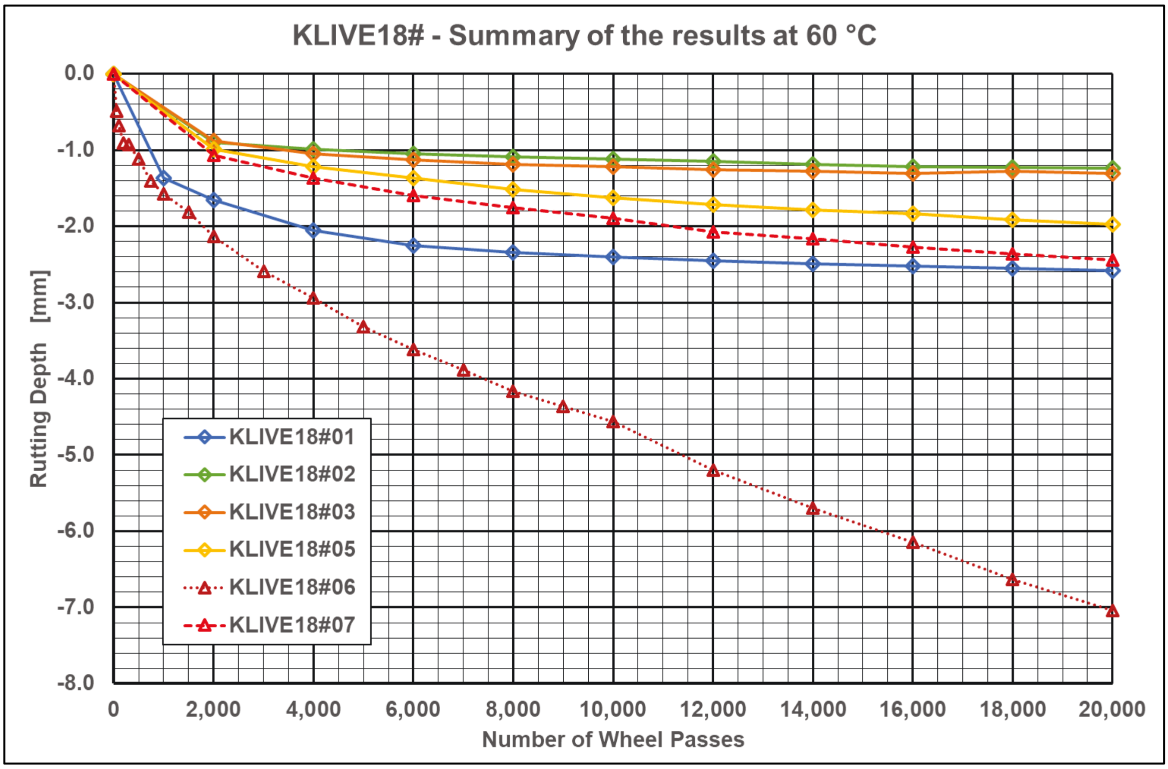


Figure 5 – summary of the results obtained from wheel tracking test at 60°C

All significant properties related to the permanent deformation resistance defined in the tendering documents are listed in Table 9.

Table 9 – WTT test results as defined by CE marking

	Rut Depth	Proportional Rut Depth	Height	Wheel Tracking Slope
	RD	PRD	Height	WTS
Navn	mm	%	mm	mm/1.000 cycles
KLIVE18#01	2.6	6.4	40	0.03
KLIVE18#02	1.2	3.1	40	0.023
KLIVE18#03	1.3	3.3	40	0.019
KLIVE18#05	2.0	4.9	40	0.070
KLIVE18#06	7.0	17.6	40	0.495
KLIVE18#07	2.4	6.1	40	0.108

WTT test results show that most of the KVS mixtures met the requirements. The only exception is represented by KLIVE18#05 due to the WTS exceeding the 0.050 mm/1000 cycles. 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. It is expected that WTT requirements will be fulfilled by all the contractors by applying small adjustments to the KVS mix design. (An additional point is that the precision of the test method with respect to WTS (Wheel Tracking Slope) has not been established, yet).

Durability test performed at Ulster University

Introduction

To further assess and verify the mixture performances, DRD has decided to include an additional test to study the durability of the textures on specimens sampled from the 6 different sections. The idea of testing specimens cored from the field is due to the need of accounting for the impact on the overall KVS asphalt production and paving.

The most feasible solution has been identified at the University of Ulster in North Ireland. The laboratory facility has an accelerated loading device, Road Test Machine (Figure 6), which allows testing samples taken directly from the field.

Figure 6 - Road Test machine at University of Ulster

The Road Test Machine (RTM) located at Ulster University was used to simulate dry, slow speed, high contact stress interaction between the test tyre and the surface texture of the core. This test is known in the UK as the Wear Test and is used as part of the certification process for testing High Friction Surfacing Systems (HFS).

The RTM consists of a 2.1 m diameter horizontal table that rotates at 10 rpm. Ten test specimens can be fixed to this table. Two vertically mounted 195/70R14 test tyres each apply a load of approximately 5 kN. Tyre inflation pressure is 30 psi. The temperature of the test room is maintained at 10 +/- 2°C during simulated trafficking. The change in surface texture related properties was determined. This investigation included skid resistance, mass loss, texture depth and visual appearance. Only the most relevant results, extracted from the report delivered by Ulster University, are included in the present notes.

The following pavements have been chosen and tested:

- SMA8 KVS (M14 – KLIVE18#01)
- SMA8 KVS (vej119 – KLIVE18#02)

- SMA8 KVS (M60 – KLIVE18#03)
- SMA11 Reference (M14)
- SMA8 Reference (M14)
- SMA8 SRS (M40)

Due to time constraints, samples from the M30 (KLIVE18#5) have not been included in the present experiment.

Change in texture depth due to simulated trafficking and percentage of mass loss

The Macrotexture depth (MPD) of each 142 mm diameter core was determined using a modified version of the volumetric patch technique (EN 13036-1:2010). The 142 mm diameter of each core meant that the standard 50 ml volume of material could not be used. The standard test method was modified to determine the mass of sand required to infill the surface texture of each core. The volume of required material could then be used to calculate a modified Macrotexture Depth.

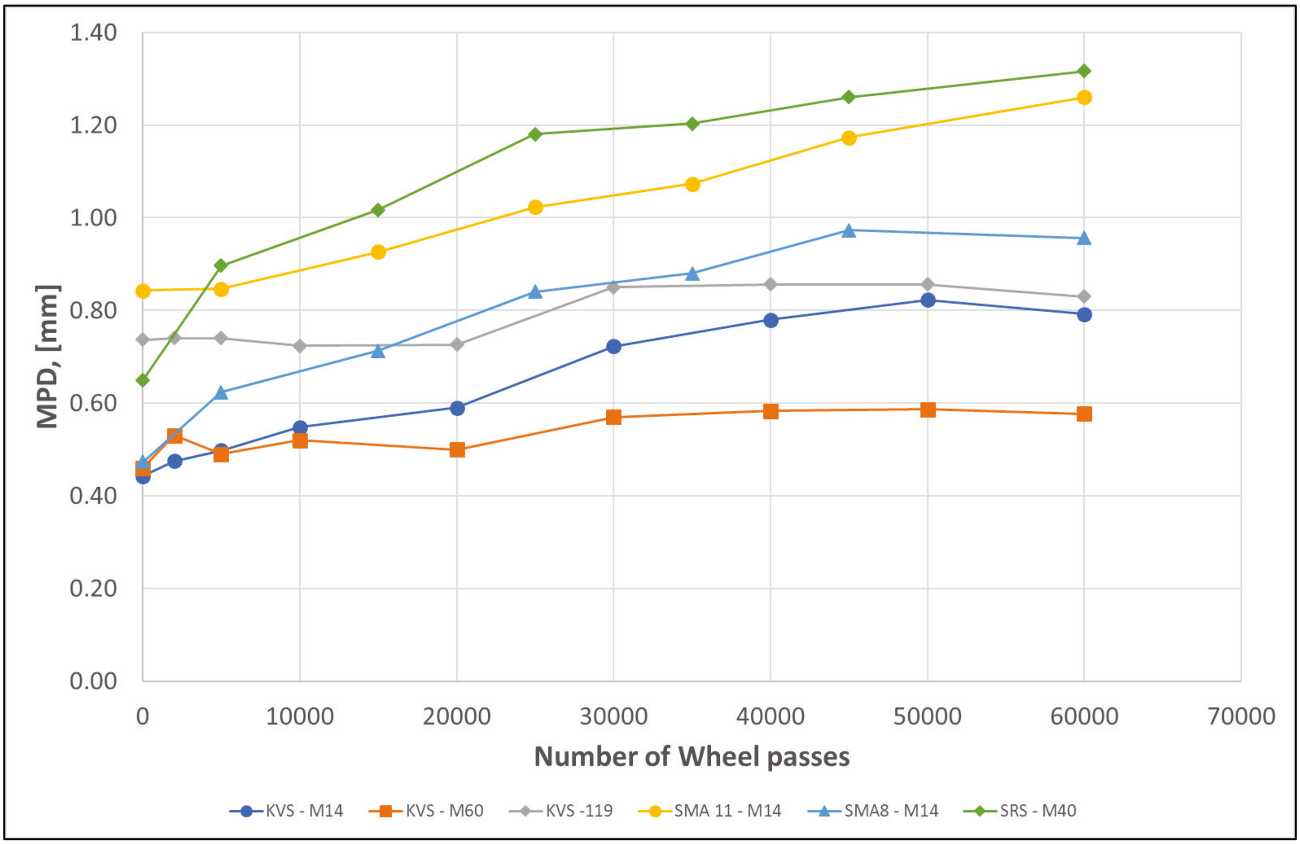


Figure 7 Plot of modified MPD data.

The change in texture depth, measured on the tested specimens, shows that KVS mixtures have a stable texture in particular when compared to conventional mixtures. These results highlight that the difference in rolling resistance properties between KVS and standard mixtures might increase with time due to the different rate of texture development.

The mass of each core was recorded after each period of simulated trafficking. This mass loss was used to calculate a percentage wear value for each core.

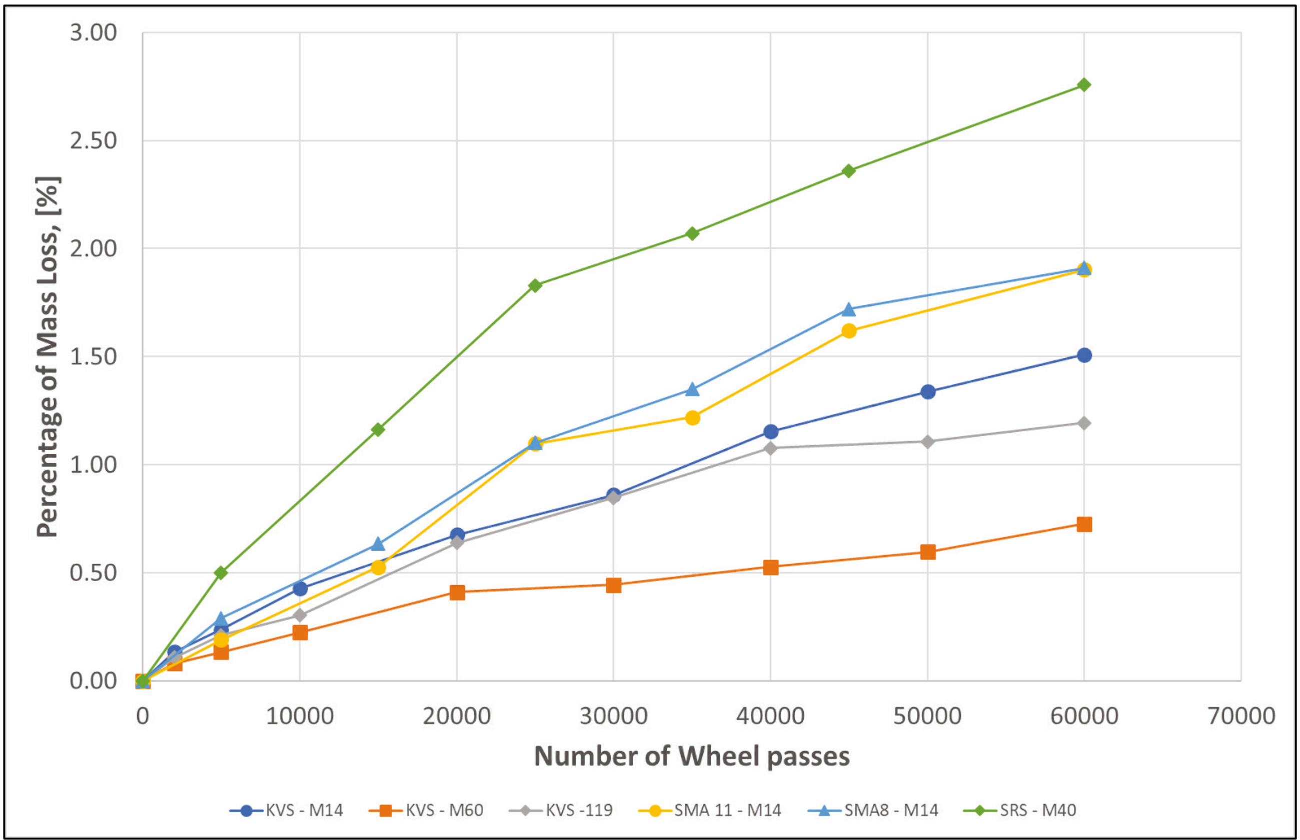


Figure 8 – Wear data calculated as percentage of mass loss

The accelerated test results obtained using the RTM confirmed what measured at VTI using the circular road test (Pettinari et al. 2018). In general, KVS pavement exhibits the most stable texture with the lowest percentage of mass loss when compared to standards SMA and SRS mixtures. To provide a more precise estimation of the expected life, it is important to monitor these sections over the coming years and compare field data to those measured on the RTM. RTM results are promising with regards to durability and it is possible to assess that the expected life time of KVS mixture should be at least not lower than what shown by standard SMA 11.

Construction quality control

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 in order to monitor the temperature of the newly paved asphalt layer as it left the screed of the paver. This has provided a thermal data set from each test site. Different technologies have been used and these are listed in Table 10. The reference name of asphalt mixtures are also included in the next table for any comparison to the the laboratory testing.

Table 10 - Road sections where thermal data was collected.

Name of road	Adm. #	Side	Lane	From km	To km	Contractor	Mix ref.	Supplier of IR system
Helsingørmotorvejen	14	R	H	41/0000	41/0520	Munck	KLIVE18#01	TF Tech-nology
Skovvejen	119	L	H	22/0373	20/0700	Colas	KLIVE18#02	Vögele
Østjyske motorvej	60	R		90/0660	92/0252	YIT	KLIVE18#03	Vögele
Sydmotorvejen	30	L	H+F	137/0000	145/0000	NCC	KLIVE18#05	Vögele

The activities completed within this phase can be categorized as a pilot project because for the first time the DRD has used thermal data collected from the paver to estimate and evaluate, using a consistent procedure, quality of the paving operations.

The main objectives of using this technology during paving operation are:

- To measure and document thermal readings of the paved HMA as it leaves the screed of the paver;
- To develop a control tool to monitor paving operations.

In fact, thermal data of the paving operations 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 to uneven surface properties and premature failure due to a lack of compaction. Thermal imaging technology was found to be an effective tool in identifying temperature segregation during paving [Louay N. et al. 2019].

The present approach is not only meant to control the contractor but has also the scope to help the contractor understanding potential problems related to production and paving by:

- making a method description that gives contractors certain degrees of freedom, allowing for the best possible outcome and learning scenarios;
- making a method description that involves iterations of feedback rounds with the involved contractors and the suppliers of the IR systems.;
- determining the needed data structure, format and output.

Thermal analysis: method description

A method description was developed. It must be considered an intermediate version (alpha) because it is key for a successful method description, to continuously keep gathering experiences from the contractors and the developers of the used technologies.

The method description was formulated in a way that it should be fulfilled by as many devices as possible. This is necessary in order to keep a focus on what has to be delivered and not forcing the use of any certain supplier in order to satisfy the task.

To meet the wish of DRD for getting proper and useable thermal data keeping an open market of suppliers, certain degrees of freedom must be allowed in the method description and this is given by an iterative process between the DRD, the contractors and the developers/suppliers of the technology.

Requirements set in the method description are so far based upon the ‘AAB for varmblandet asfalt’ and the capability of several different suppliers measuring systems.

The key feature of the method description is to first and foremost give a clear picture of the data that is to be delivered and respective requirements.

A version of the method description for Thermal Profiling has been drafted and included in the tendering material for the upcoming project on Haderup Omfartsvej (Annex E).

Algorithm development

To get this process started, a code was developed to identify surface areas that are inhomogeneous in temperature. Two fundamental inputs must be defined and used to process thermal data:

- Critical temperature gradient (ΔT): temperature difference between two adjacent areas;
- Cessation temperature (C_t): temperature where compaction is no longer possible.

Using these two temperature inputs, the data can be processed, and the outcome is represented as example in the Figure 9. In this specific case, a temperature gradient of 14°C was used and 80°C was defined as cessation temperature. Both temperatures must be defined in relation to the asphalt mixture properties.

The developed algorithm is accessible by the following link “https://github.com/roadtools/roadtherma”. The code firstly trims the raw thermal data:

1) by identifying and removing any area and foreign objects with a 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 quality of the paving operation;
2) by removing portions of the longitudinal joints that were measured but belonging to existing surfaces scanned by the thermal device;
3) From the trimmed data, the code identifies and calculates how much area in the percentage exceeds ΔT (in relation to any given temperature input) and generates a plot.
4) Additionally, the temperature distribution of the surface area is calculated and plotted, cf. example from the paving operation at Helsingørmotorvejen in Figure 10.

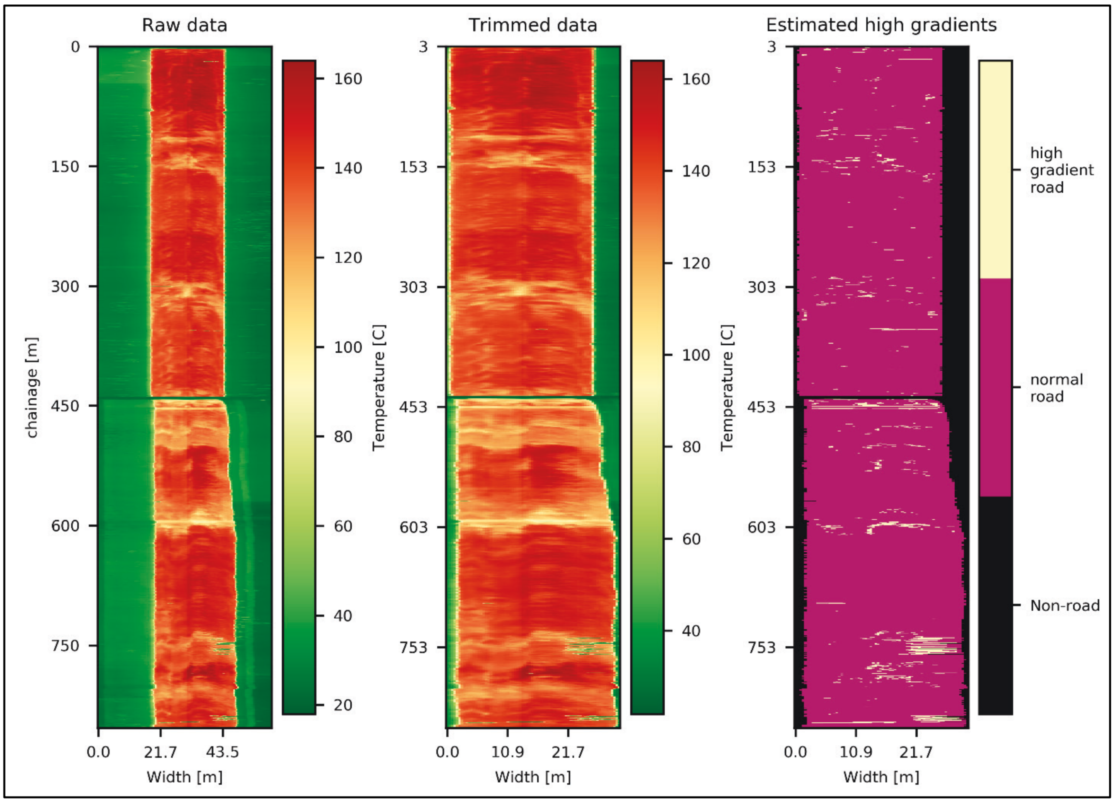


Figure 9 - Plot of raw data and plot of trimmed data. Example from operations on M14.

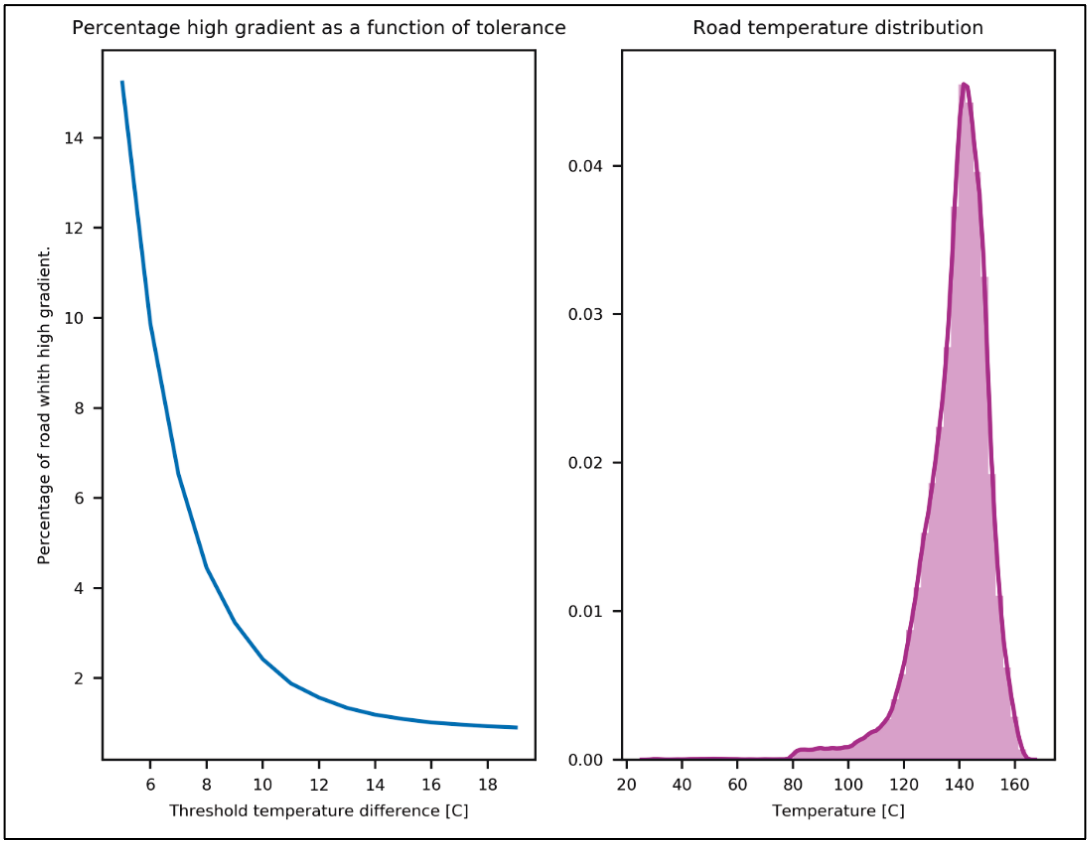


Figure 10 - Plots of percentage of surface area exceeding critical temperature levels in relation to potentially critical threshold temperature and plot of temperature distribution. Example from operations on M14.

The developed code should be considered an alpha version and further investigation is requried. Thermal analysis represents an optimal solution to improve quality control and motivate contractors to focus on paving operations. The possibility of gaining more experience with this type of technology must be considered because the benefit related to the use of these data type is significant in particular when even surface properties and durability are demanded (Williams C. R. et al., 2016). In the next paragraph, all the data collected during the construction of the KVS sections are represented.

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 the temperature variability. Furthermore, by using the developed algorithm, it was possible to estimate a percentage of the paved area which did not satisfy the temperature gradient criteria. Different temperature gradients were studied.

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 further investigate the possibility of implementing this technology, it is highly recommended to compare the two devices over the same surface and compare the outcome of the developed algorithm.

Considering the collected data, the following relevant information must be listed (Table 11).

Table 11 – Differences between the construction sites and thermal devices used

Section	Job (day/night)	paver type	feeder (Yes/No)	Thermal Device
M14	night	lane width	No	TF technology
119	night	lane width	No	Vogele
M60	night	lane width	No	Vogele
M30	day	full width	Yes	Vogele

Table 11 confirms that there are several variables on each construction and it won't be possible to establish to what degree the variables have affected the results.

Figure 11 summarizes the analysis of the paving temperatures in a histogram over the distribution between 80°C and 180°C considering 10°C intervals. The results show that the section paved on the M30 during the day and using the 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 mix design properties, having a big percentage of the paved area within 150 – 160°C increases the risk of drain down problem. M60 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 is very difficult to work because of the way it has been designed 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).

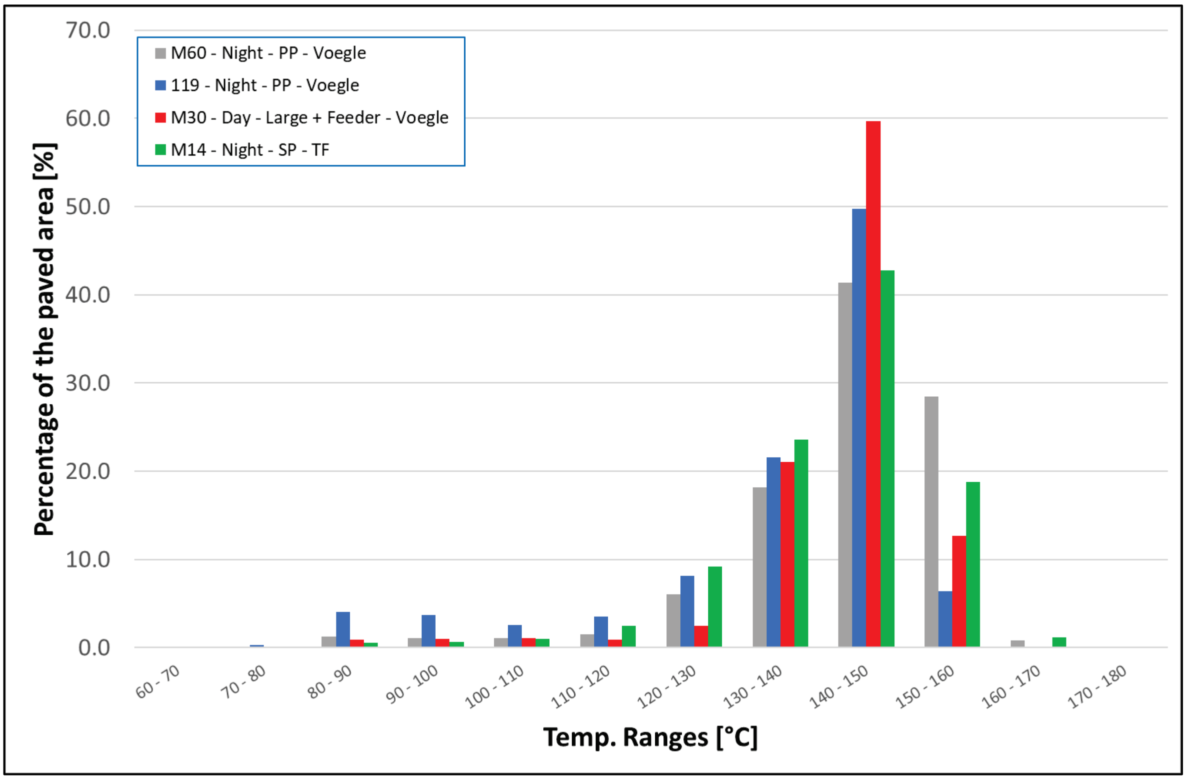


Figure 11 – Temperature distribution of the paved KVS sections

Figure 12 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. M30 and M14 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 the higher is the chance to have segregation in the mixture.

It is recommended to monitor the asphalt properties over the coming years to understand and prove the reliability of the analysis. It would be beneficial also to drill some additional cores on those areas where a high temperature gradient was measured to verify if there are differences in mixture properties and air voids.

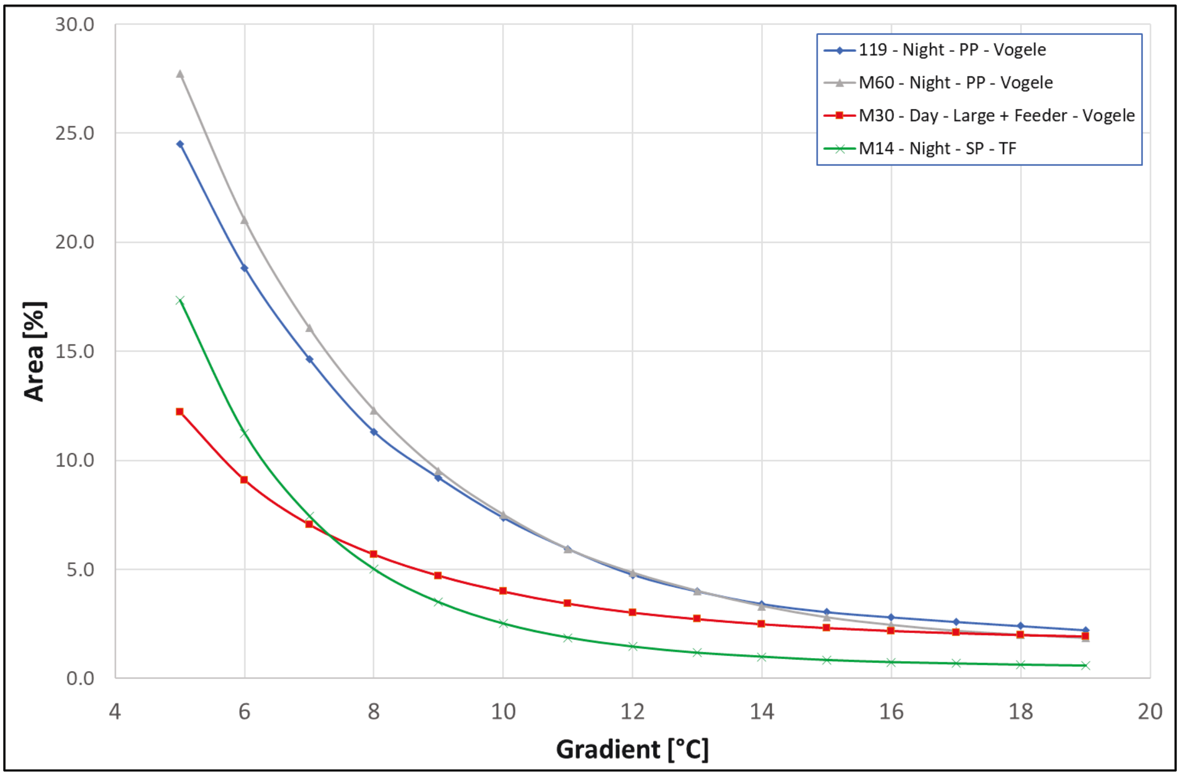


Figure 12 – Temperature gradient and relative percentage of area

Quality control using functional measurements

Additional information about the quality of the paving operations can be made studying the functional properties of the finished layer such as:

- MPD;
- IRI;
- Friction.

In this specific case, friction measurements appear to be relevant. In fact, KVS asphalt mixtures are very rich in fine aggregates and binder and if these fines are not properly mixed and/or the quality of paving operations does follow specific criteria (due to paver problems or production temperature) then two issues will be detected in the field:

- Friction at 60 km/h on left or right wheel path after one week will be higher than 0.35;
- Ratio between Min and Max friction will be higher than 0.7.

This criterion seems able to establish the quality of the paving even if it is recommended to further investigate which limits should be used. These limits have been defined based on 4 different sections consequently it is recommended to further investigate this criterion on a bigger sample of new constructions.

The above described method has been applied on the following sections:

- M14 (Figure 13);
- 119 (Figure 14);
- M60 (Figure 15).

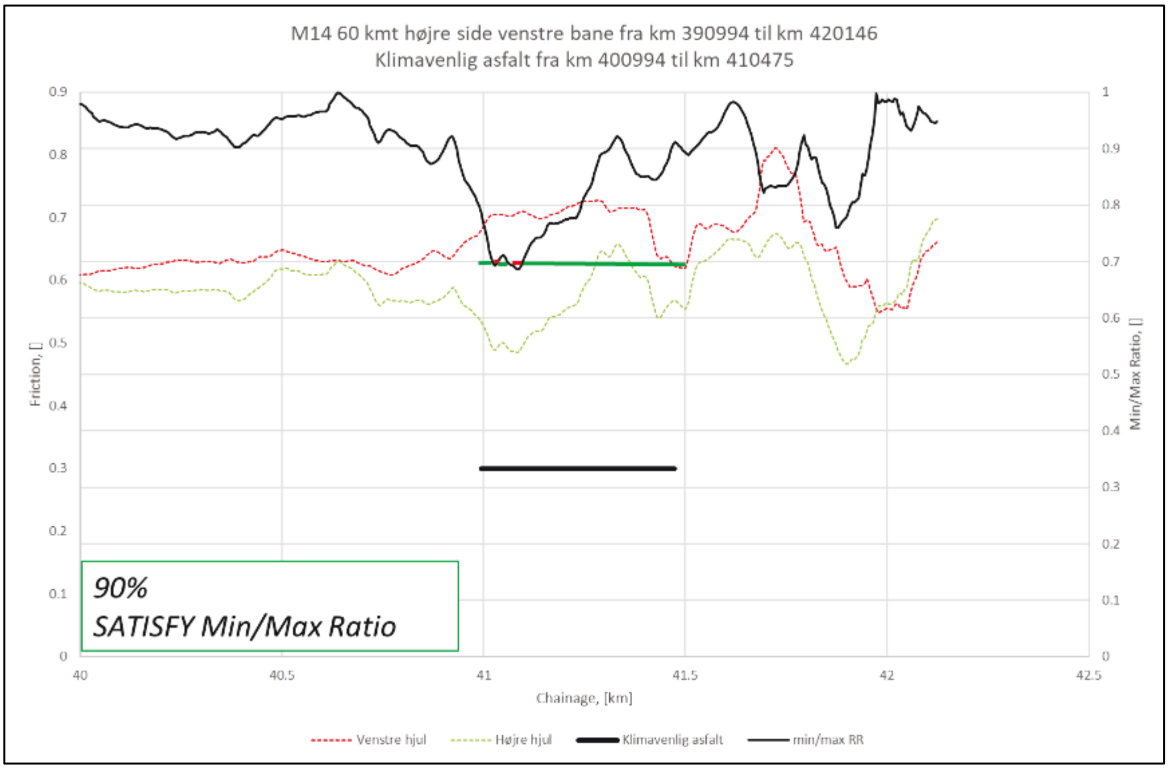


Figure 13 - Surface quality using friction data on M14

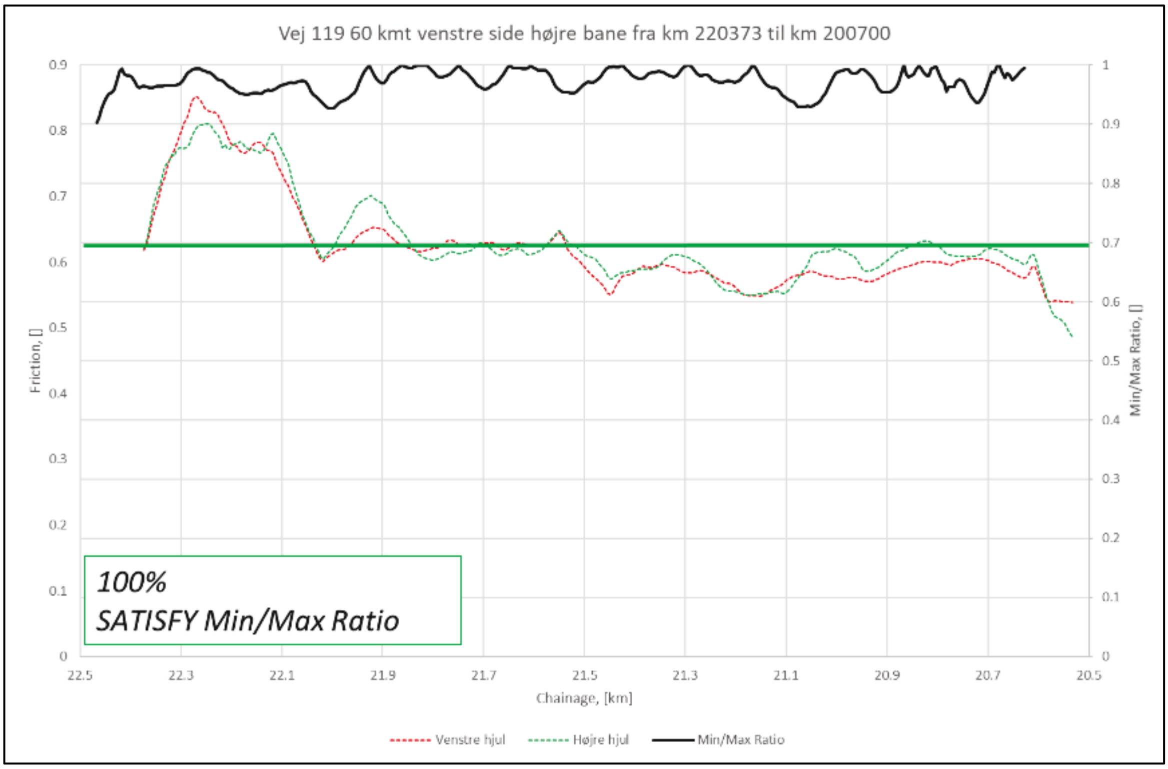


Figure 14 - Surface quality using friction data on Vej 119

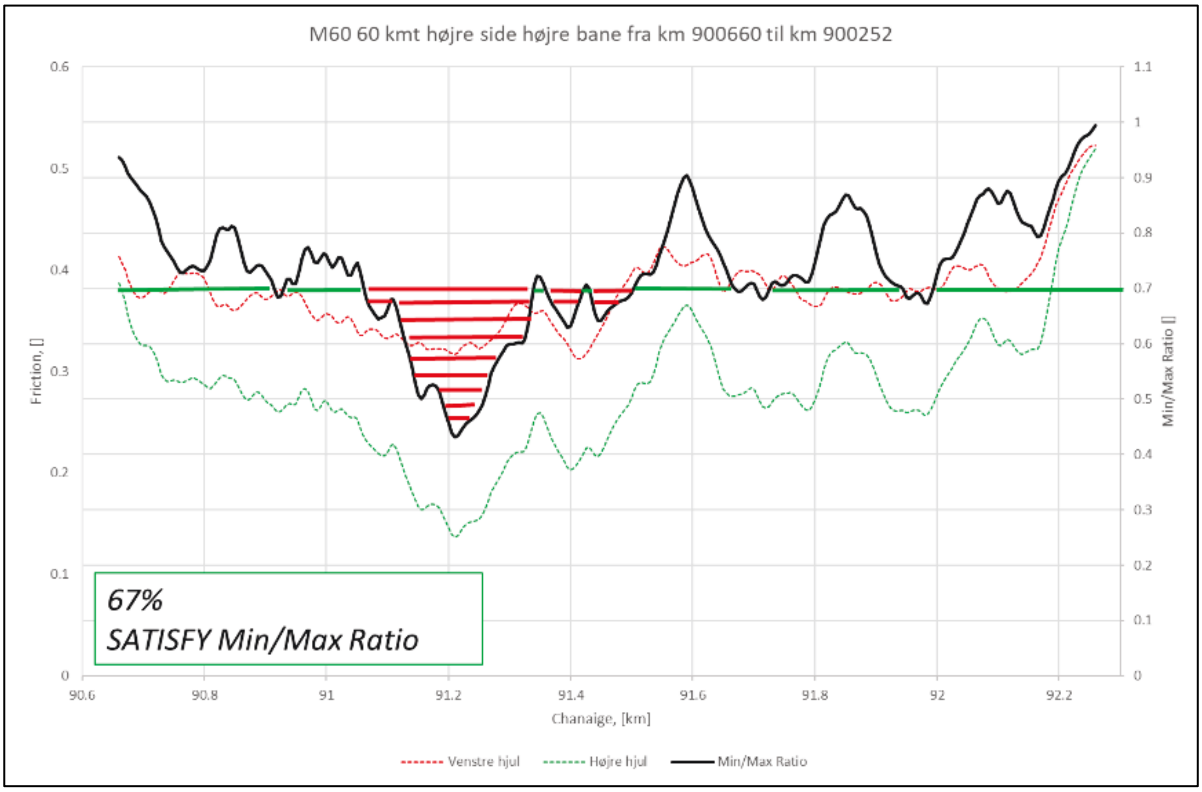


Figure 15 - Surface quality using friction data on M60

With regards to friction characteristics and development of the KVS pavements, it must be acknowledged that within the specifications the same pavement type can be produced by different contractors with relevant difference in fines content and consequently MPD. This aspect influences the friction characteristics and measurements. Friction on route 119 can be explained by looking into the average low compaction temperature and a mix design with a lower content of fines and bitumen compared to the other studied cases. Basically, their mix type is closer to an SMA8 standard and this is the reason why the MPD is 0.65 mm.

In general, standard friction development cannot be applied on KVS mix type because it is normally produced with a high content of high polymer modified bitumen and fine gradation. The following remarks need to be accepted if DRD wants to proceed with the implementation of KVS mixture on a network level:

- The thicker coating of the mortar makes this mix type more slippery at the beginning compared to standard SMA8 or SMA11.
- The rate of development of friction to a stable level is longer compared to standard SMA8 and SMA11.
- Stability of the friction measurements are affected by the mix properties and it will take longer time before the friction will be even on the pavement along the longitudinal direction.

Analysis of the functional properties

The functional properties included in the investigation are listed below:

1 Mean Profile Depth (MPD), parameter used to quantify pavement macrotexture, is calculated by dividing the measured profile into segments with 0.1 m length. A linear regression of the segment is subtracted from the corresponding measured profile to remove the slope and provide a zero-mean profile. Every segment is then divided into two parts of 0.05 m and for each part the peak value of the profile is determined. The two peaks and the mean value are used to calculate the MPD and equation is described in the reference standard ISO 13473-1;

2 International Roughness Index (IRI) is measured using a standardized profilometer. IRI was on both wheel path using the quarter model car. An average value of the IRI was recorded every 10 m.

3 The friction properties of the test section were monitored using the VIAFRIK following the CEN/TS 15901-5. A fixed slip ratio of 20 % between the measuring wheel and the speed of travel was used. Friction coefficient is given as mean friction coefficient at any 100 m stretch. Measurement is done at 60 km/h. However, on lines with lower permissible speeds, measurement can be performed at either 40 or 50 km/h as indicated in the table below. The mean friction coefficient value "F" for each measuring wheel must comply with the following requirements when measuring at a constant speed (Table 12):

Table 12 - Surface layer, measurement speed and friction coefficient

	Meas. Speed	Friction (F)
Road with speed limit < 50 km/h	40 km/h	F >0.50
Road with speed limit 50 km/h	50 km/h	F >0.45
Road with speed limit between 60 - 80 km/h	60 km/h	F >0.40
Road with speed limit > 80 km/h *)	60 km/h	F >0.50

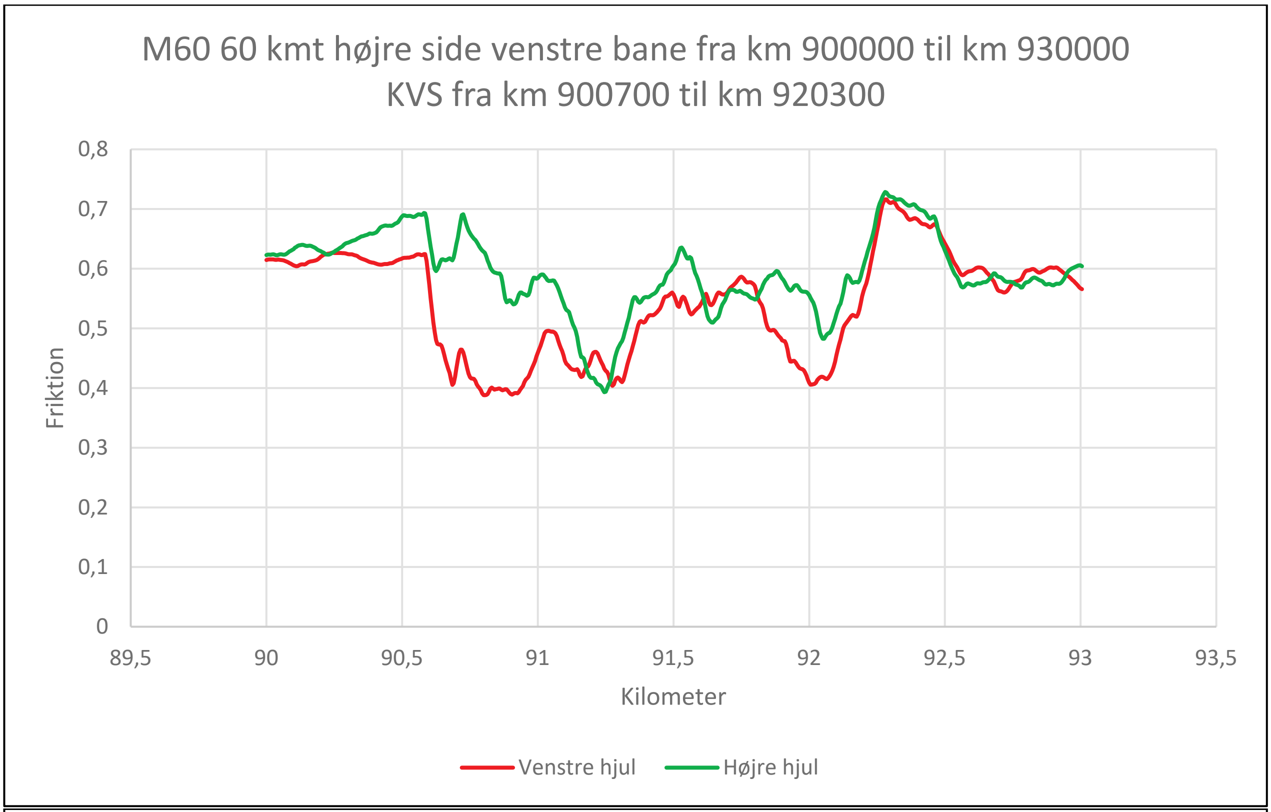
*) On roads with a permitted traffic speed above 80 km/h, an additional measurement can be performed at 80 km / h. The result of this measurement must not be more than 0.10 lower than at 60 km / h. The two measurements are made immediately after each other.

Table 13 gives a summary of the values for the individual parameters for each section. Note that MPD for the M30 is under evaluation, possibly due to the defect on the texture lasers, and that the wearing course on the M60 and some wearing courses on the M30 do not meet the requirement for friction, comparing the road rules for the hot mix asphalt.

The friction on the M14 is indicated (F> 0.4) as there is a speed limit of 60 km / h on this section of the motorway. Likewise, it applies to route 119, which is a main road, with a limit of 80 km / h.

Road		Lane	Section	Av. IRI left wheelpath	Av. IRI right wheelpath	Av. MPD left wheelpath	Av. MPD right wheel-path	Friction 60 km/h
			From km - to km	m/km	m/km	mm	mm	Accepted / Not accepted
M14	Right	Right	km 400994 - km 410475	0.92	1.39	0.53	0.47	Accepted (F>0.4)
M14	Right	Middle	km 400994 - km 410475	0.89	0.91	0.45	0.46	Accepted (F>0.4)
M14	Right	Left	km 400994 - km 410475	1.00	0.96	0.46	0.48	Accepted (F>0.4)
M14	Left	Højre	km 410520 - km 410000	1.09	1.46	0.47	0.49	Accepted (F>0.4)
M14	Left	Middle	km 410520 - km 410000	0.96	0.94	0.52	0.47	Accepted (F>0.4)
M14	Left	Left	km 410520 - km 410000	1.02	0.94	0.49	0.47	Accepted (F>0.4)
M30	Right	Right	km 1370545 - km 1440020	0.64	0.74	0.84*	1.24*	Accepted (F>0.5)
M30	Right	Left	km 1370545 - km 1440020	0.67	0.70	0.76*	1.30*	Accepted (F>0.5)
M30	Left	Right	km 1430400 - km 1390495	0.69	0.81	0.76*	1.11*	Partially not accepted F<0.5
M30	Left	Left	km 1430400 - km 1390495	0.68	0.74	0.67*	1.10*	Partially not accepted F<0.5
M60	Right	Right	km 900660 - km 920252	0.87	0.87	0.68	0.78	Mostly not accepted F<0.5
M60	Right	Left	km 900660 - km 920252	0.69	0.66	0.61	0.81	Mostly not accepted F<0.5
Vej 119	Left	Right	km 220373 - km 200700	1.04	0.97	0.76	0.87	Accepted (F>0.4)
Vej 119	Left	Left	km 220373 - km 200700	1.02	0.94	0.70	0.86	Accepted (F>0.4)

Table 13 – Summary of the functional measurements collected by DRD after 6 weeks from the paving operations. *data not reliable due to technical problems



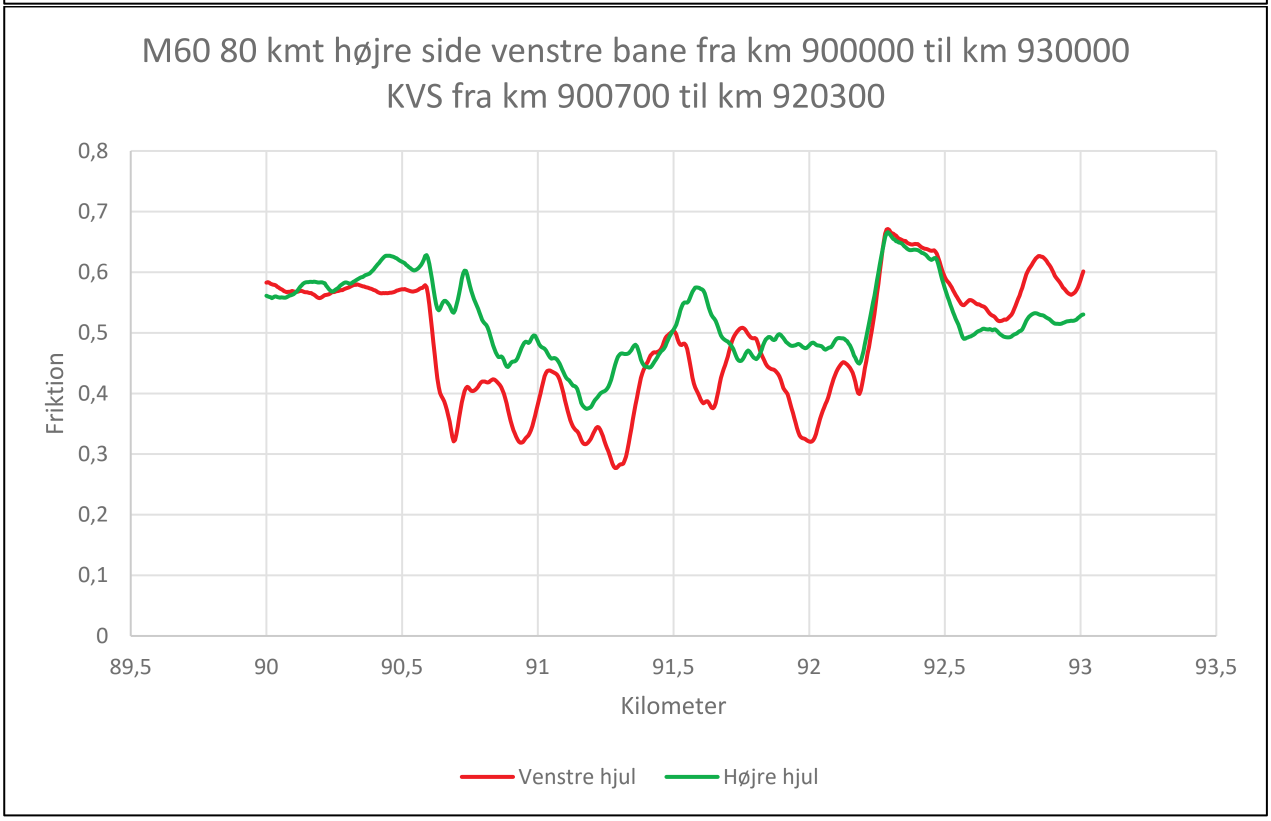
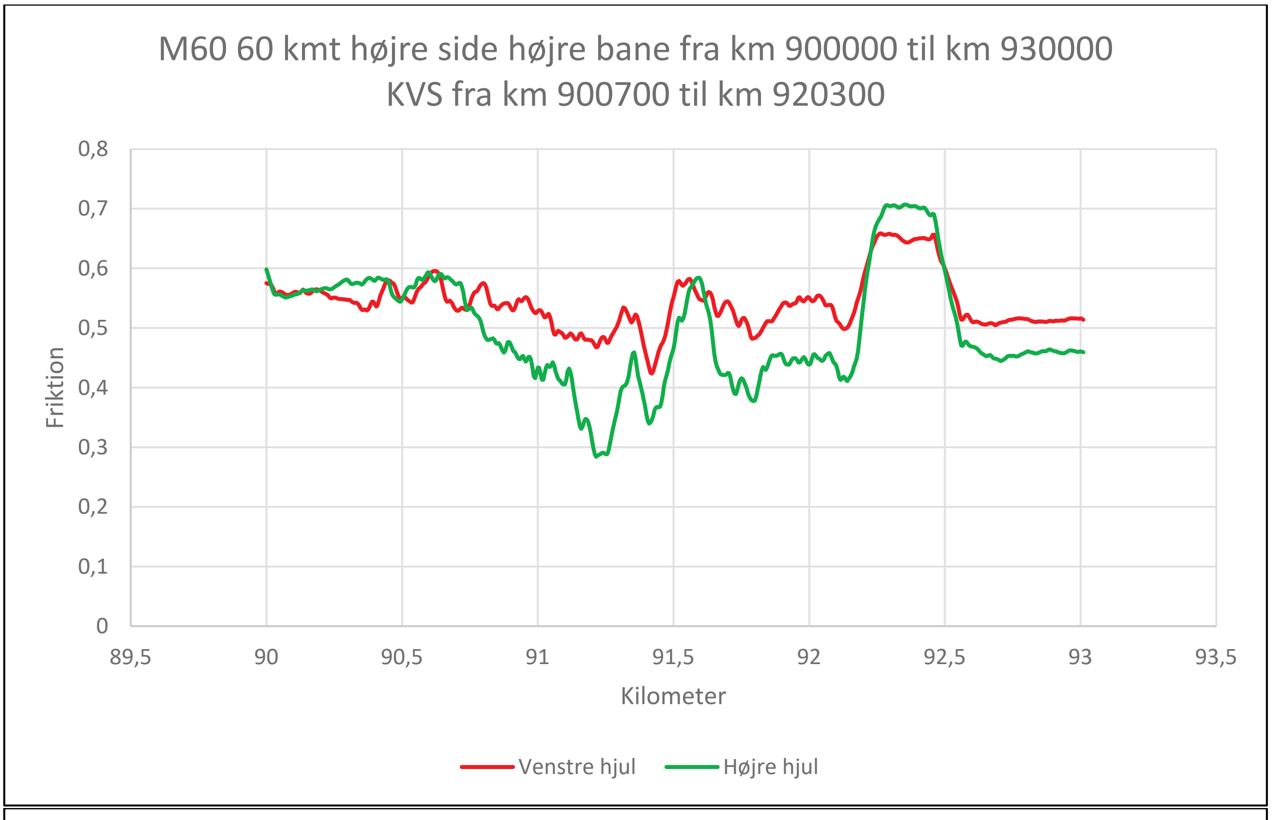


Figure 16 – Friction on M60, right side and left lane at 60 (top) and 80 km/h (bottom).



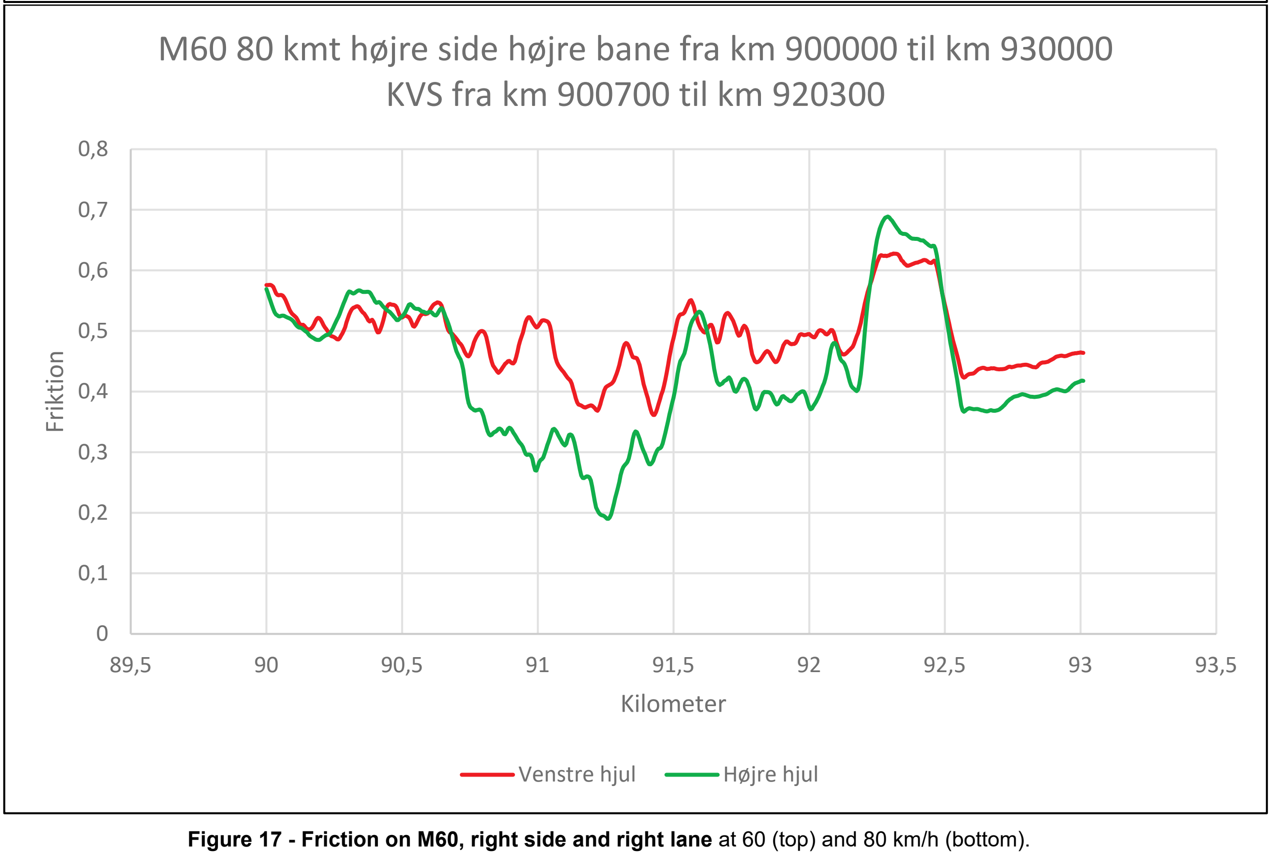


Figure 17 - Friction on M60, right side and right lane at 60 (top) and 80 km/h (bottom).

Figure 16 and Figure 17 show that the friction requirement (F> = 0.5), was not met for most of the section. In this particular case, a warning sign (slippery road) was placed in proximity of the section. The date of the above measurements was December 10, 2018. Friction measurements were repeated during spring confirming what was observed in December. It has been established that the surface of the KVS section on M60 will be water blasted to increase texture depth and rise friction properties.
Additional measurements of the MPD and IRI were completed in April 2019 and the results are described in the next paragraph.

Surface characteristics measured in April 2019

The texture of the road surface was measured using the M+P FLaSH|M texture measurement system. Every millimetre of travelled distance the height is registered. Laser specifications are listed below:

- Type: LMI Gocator 1340, laser class 3B;
- Sample distance: 1 mm;
- Measurement range: 210 mm;
- Resolution: < 1 µm.

The laser data have been used to measure both IRI, MPD and Skewness. Data from the M14 could not be included due to practical reasons (traffic conditions, traffic light nearby, etc.).
Figure 18 includes IRI values measured on M30, M60, 119 and includes both KVS and SMA11 mixtures.

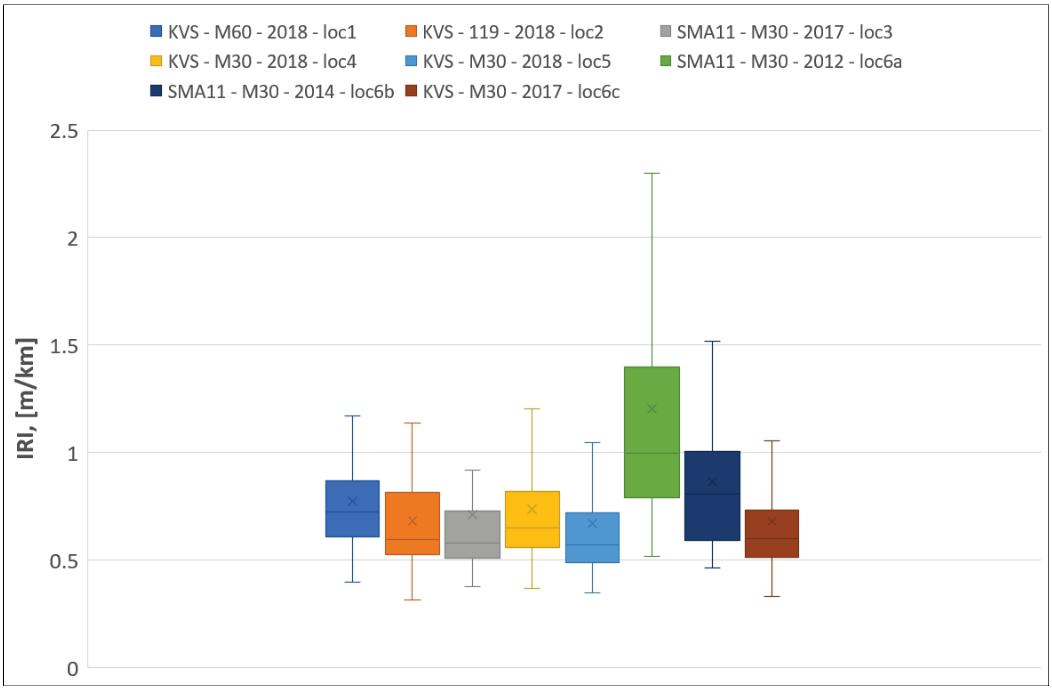


Figure 18 – IRI measured in April 2019 by M+P

Vejdirektoratet

Data confirm that IRI is not material related, but it is a property linked to the pavement structure and construction type. Average IRI values on KVS pavements are between 0.6 and 0.75 m/km.

Figure 19 shows the MPD values measured on M30, M60, 119 and includes KVS and SMA11. Average MPD value measured on KVS pavement type was approximately 0.5 mm. Average MPD value does not include in this case data obtained on 119 and M60. In the first case, pavement type and texture were very similar to a standard SMA8. MPD on M60 is much lower than what experienced in the other sections and trials, due to both mix design limitations and challenges faced during construction.

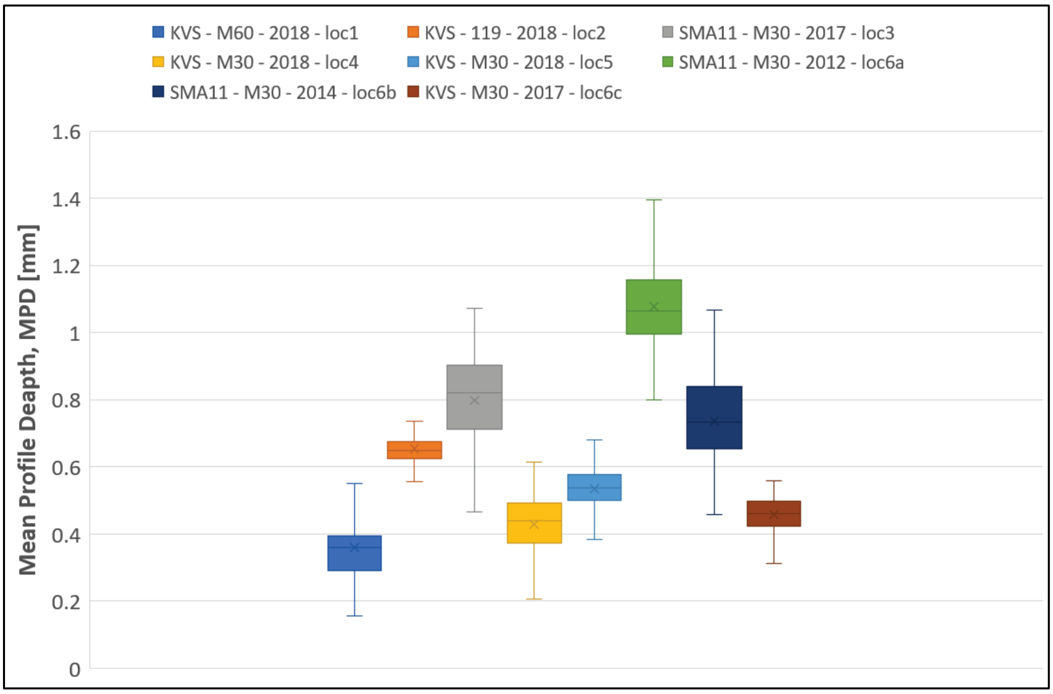


Figure 19 – MPDs measured on KVS pavement and

Skewness of the profile (Rsk) is a dimensionless measure of the asymmetry of a statistical distribution about its mean. Skewness is a measure of interest because, when it is applied to pavement-texture profiles, it allows distinguishing between positive- and negative-oriented textures. *Rsk* is calculated as follows (1)*:*

$$Rsk = \frac{1}{Rms^3}\left[\frac{1}{l}\int_0^l Z^3(x)\,dx\right] \qquad (1)$$

where *Z(x)* is the ordinate value representing the texture-profile height (mm), *Rms* is the root mean square value of *Z(x),* and *l* is the evaluation length (mm).

Figure 20 summarizes the Skewness values measured on the studied test section. In general, all KVS mixtures have lower Rsk than those measured on SMA11.

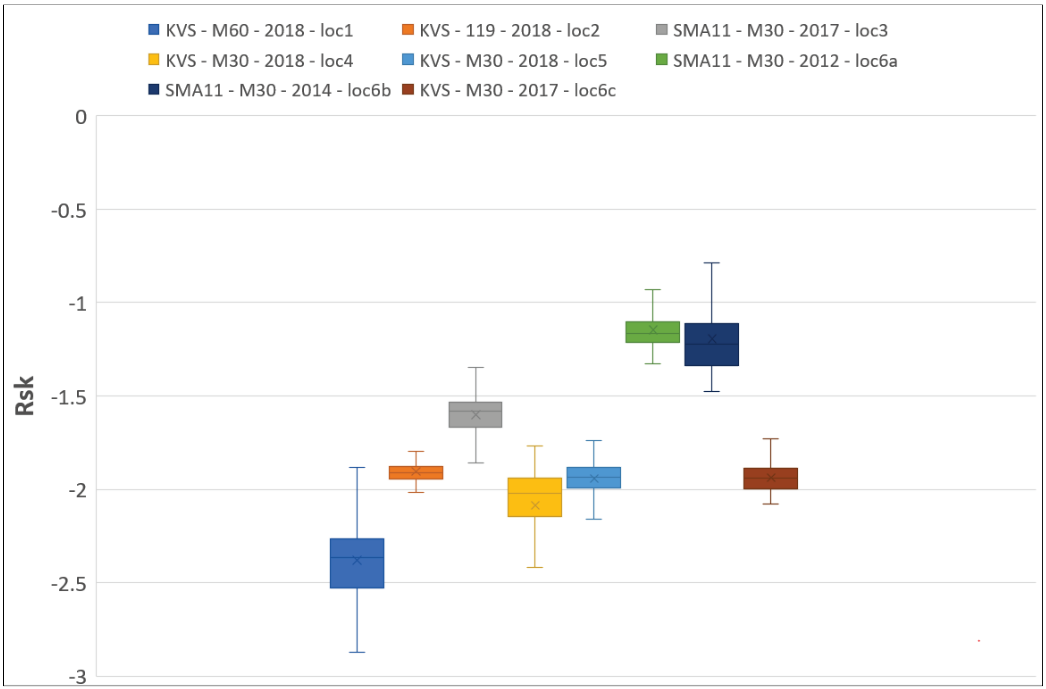


Figure 20 – Skewness data measured on M30, M60 and 119.

Noise measurements on KVS pavements

Only one contractor had some experience because involved as partner in the projects COOEE and ROSE (Pettinari et al. 2016a, 2018)

Apart from the section paved on the M30, all the other sections were paved by contractors which did not have any experience with this mix type. It must be acknowledged that some contractors faced some challenges which resulted into some variability of the finished layer. It is expected that this variability which influences the noise emissions of this pavement type, should reduce as function of:

- time;
- experience of the contractor with this pavement type and
- longer sections.

The CPX method was used to perform noise measurements on the Danish test sections with climate friendly, standard SMA 11 and noise reducing pavements (SRS) having similar life time and traffic conditions [ISO/CD 11819-2:2017:]. 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 80 km/h. In the following, a reference speed of 80 km/h was selected for the presentation of the results, as it is then possible to compare the results from all test sections at this reference speed. Noise measurements are summarized in the table below (Table 14). Noise reductions and emissions on week 34 were interpolated when real measurements were not available. Noise reduction is referred to average noise emission of standard SMA11 after 7.5 years. Based on the noise data, it is possible to highlight that KVS pavements have lower noise emissions than SMA11 and comparable to standard SMA8. Furthermore, based on the enhanced texture stability, KVS pavement has a lower increasing rate of noise emission over time than standard SMA11 and SRS (Figure 21).

Table 14 CPX noise level at 80 km/h for the KVS when the surfaces were six months old

Road id - year - Pavement type	weeks	Noise reduction [dB]	Noise emission [dB]
119 - 2018 - KVS	6	1.0	99.6
	34	1.6	98.9
M30 - 2018 - KVS	6	1.5	99.1
	34	1.3	99.3
M30 - 2017 - KVS	6	2.3	98.3
*	34	2.2	98.4
	70	2.0	98.5
M30 - 2017 - SMA11	6	1.6	98.9
*	34	1.3	99.2
	70	1.0	99.6
M40 - 2018 - SRS	6	3.1	97.5
*	34	1.7	98.9
	42	1.3	99.3
* interpolated			

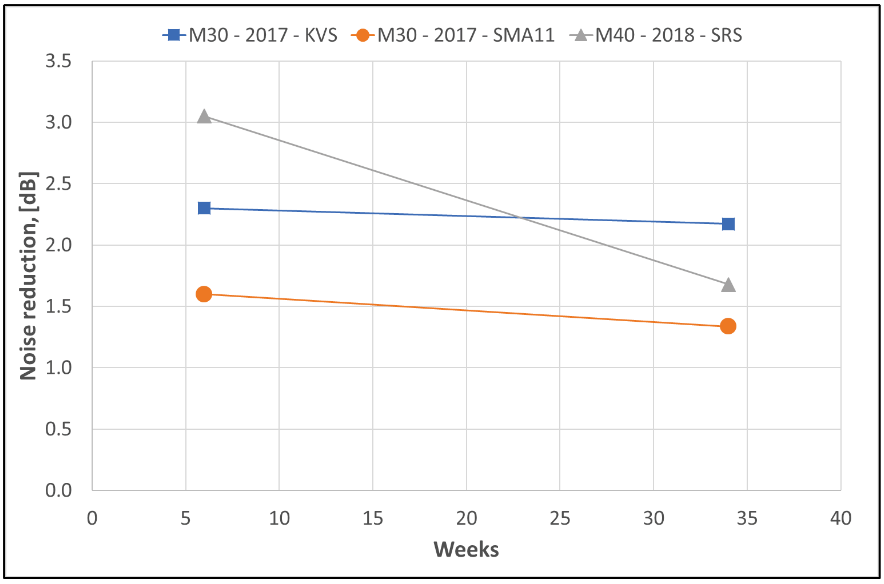


Figure 21 – Noise development from week 6 to week 34, KVS (M30-2017), SMA11 (M30-2017), SRS (M40-2017)

Evaluation of the KVS noise spectra compared to SRS and standard SMA pavement

Figure 22 shows all the noise spectra measured using the CPX trailer on KVS pavement type. As reference the noise spectrum from a noise reducing thin surface layer SMA 8 SRS (Danish abbreviation SRS – StøjReducerende Slidlag), eight years old, paved at Highway 145 is shown.

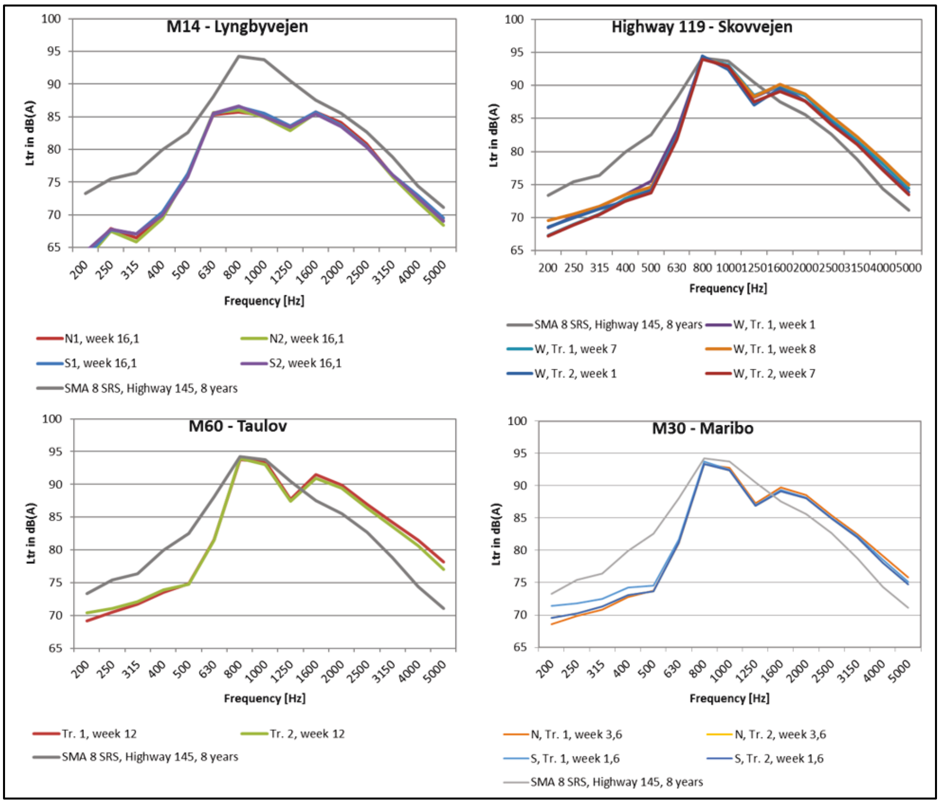


Figure 22 - Noise spectra from KVS pavements measured with CPX trailer in 2018

All the sections were monitored with all the standard vehicles to measure texture depth (MPD), roughness (IRI), friction, rolling resistance (RR) and noise. Noise was measured by the DRD while the data were processed and analysed by a consulting company [Delta report]. The noise spectra of the KVS pavements show that this pavement type differs significantly from both standard and SRS stone mastic asphalt mixes with 8 mm as nominal maximum aggregate size (NMAS).

A result, consistent with what obtained in 2018, was also measured in 2016, when NCC paved the first KVS pavement in Kalvehave (Figure 23) during ROSE project [Bendtsen et al, 2018].

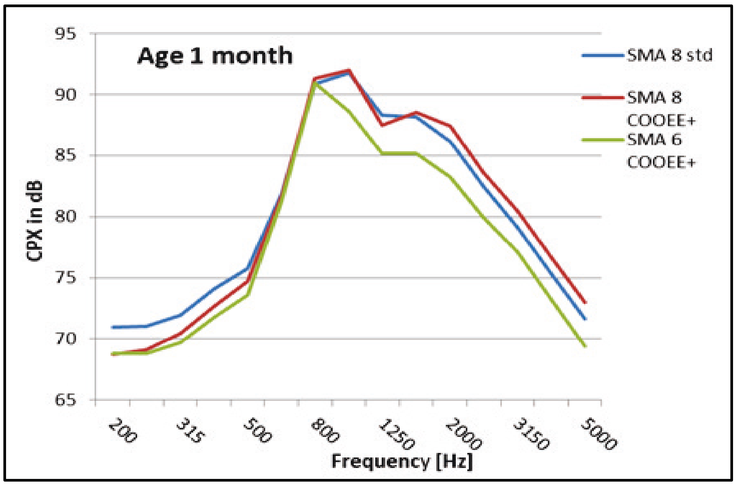


Figure 23 Noise spectra from KVS pavements measured with CPX trailer in 2016 on KVS paved in Kalvehave.

Noise spectra of KVS pavements have a very similar shape which can be described as follow:

- At low frequency range, lower noise impact than standard SMA8 or SRS (7 years old);
- At medium frequency range, standard SMA8 and KVS have similar behaviour. On the KVS paved in 2018, that peak level seems a bit higher compared to what was measured on Kalvehave and this aspect must be further investigated. Several elements affect the noise emissions and measurements, and these have not been investigated separately so it is difficult to establish what has caused this difference.
- At high frequency range, the noise of the KVS pavement seems similar to a standard SMA8.

It must be mentioned that noise measurements performed in 2018 have not been performed at the optimal pavement or temperature conditions on the M30. The M30 was paved late October 2018 and the surface properties were not optimal because this pavement type needs longer time than standard and SRS types to stabilize. 6 weeks is a valid interval of time with standard and SRS mixes. KVS mix does not belong to that class because it has high content of high polymer modified bituminous mortar and it might take longer time (traffic) before the surface texture stabilizes. Furthermore, several significant variables, such as temperature of the pavement and moisture, might have influenced the CPX data. These observations address towards the need of further investigations.
In general, the noise spectra of a KVS pavement type seems very different from standard SMA or SRS. This is expected to have an impact also in the development of the noise emissions over time. Further description of the expected development of noise emissions related to KVS are provided in the following section.

Expected KVS Noise mechanism and development
The KVS pavement type is similar to a standard SMA 8 when considering aggregates gradation. The filler components have been selected with the goal of producing a stiff mortar to increase wearing

resistance and better support of the aggregate skeleton. Air Voids content (AV), defined by the specifications, does not differ from standard mix type. KVS has high content of highly polymer modified binder which exhibits higher adhesion characteristics compared to standard binders. These fundamental mix properties have been designed to improve mix durability but have an impact on initial noise emission and noise development.

In the figure below (Figure 24), the noise spectra of a KVS pavement has been described trying to define mixture characteristics and their relative impact on noise.

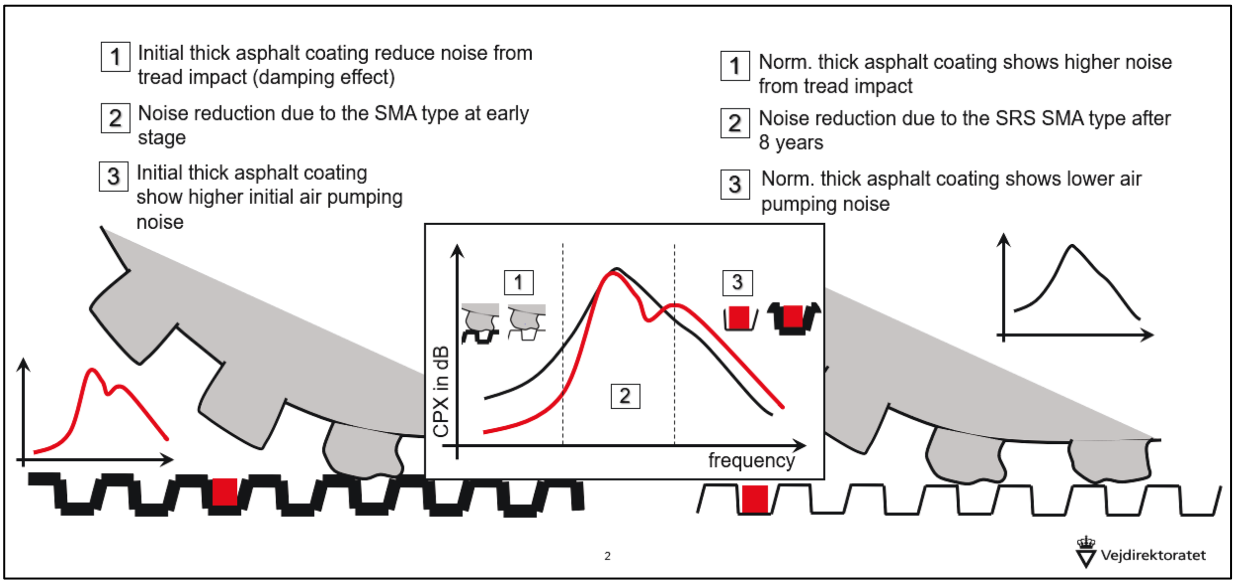


Figure 24 - Description of the expected noise mechanism produced by KVS compared to conventional mixes

The gradation of the KVS mix does not differ much from a standard SMA 8 mixture and so the voids content. This will reflect in the skeleton structure of the layer, as drafted in Figure 24. The main difference is related to the mastic and thickness of the binder coating around the aggregates. A thick coating should affect, in particular at the beginning, the voids in the texture while the higher wearing resistance of the KVS influences the change of the texture and relative voids over time. This might result into a slightly higher noise during the early stage of the pavement life span but a completely different development over time. The previous hypothesis that noise of the KVS pavement will develop as a standard SMA 8, SMA 11 or SMA 8 SRS might not be correct. This new observation must be documented and verified by following the development of the noise spectra of the SMA 8 KVS in the future.

Since KVS has a demonstrated long lifespan, also measured in the functional property of noise, the noise measurements as shown in Figure 21 are employed in to model the further noise development for KVS over the lifespan and compare to SMA8, SMA11 and SRS. This modelled noise development for KVS is visualized in Figure 25, including the comparison with SMA8, SMA11 (included as the standardized reference for noise comparisons) and SRS. The SMA8 and SRS are included with average figures of measurements conducted for each respective pavement type on the current paved stretches with these pavement types

The results, as shown in Figure 25, suggest an increasing noise reduction for KVS during the lifespan relative the other pavement types, particularly in relation to SRS and SMA11.

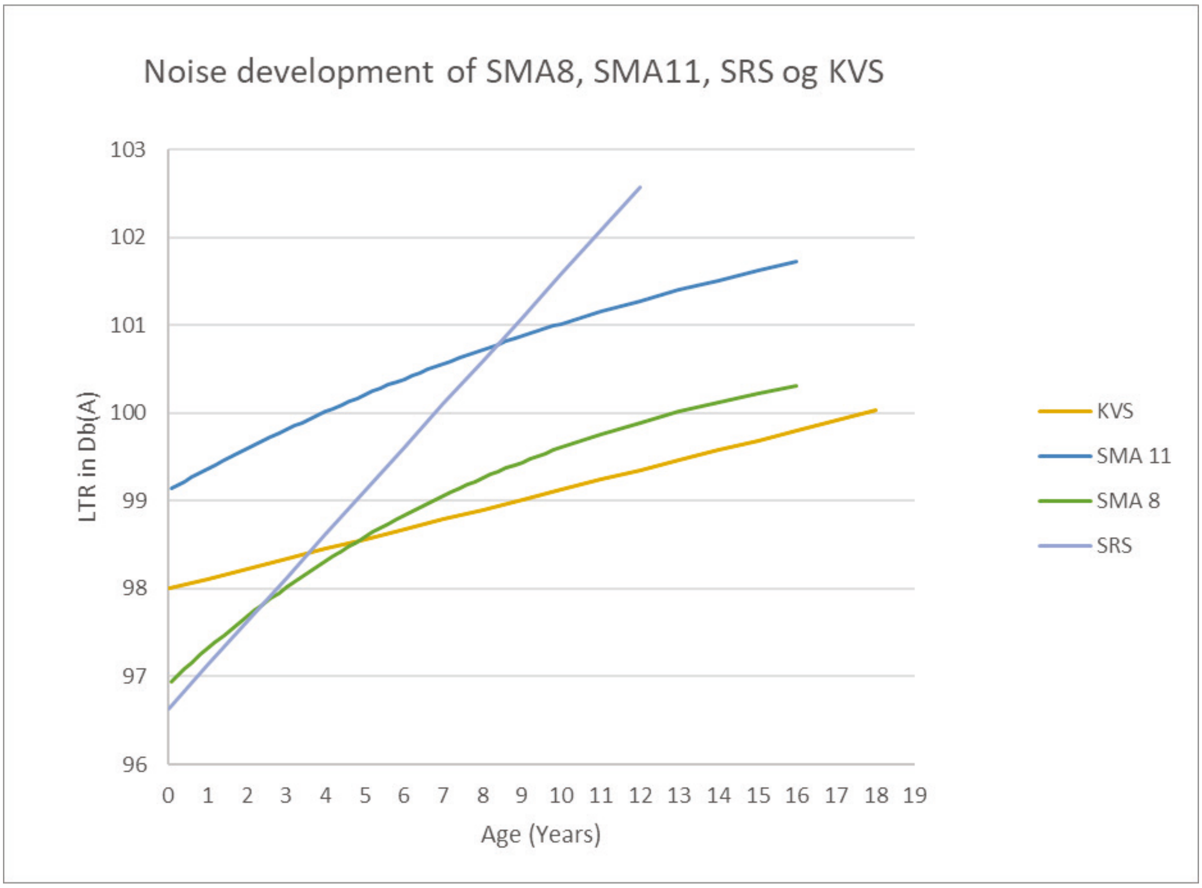


Figure 25 – Graph depicting the noise development over time for KVS relative to an SMA8, an SMA11 and the SRS

How the noise emission for KVS on the paved KVS-stretches will develop over time will be monitored closely and frequently in the coming years to document the functional characteristics in this regard and to compare these results to other pavement types.

Measuring Rolling Resistance and Fuel consumption

Description of the TUG trailer

The TUG trailer (Figure 26), developed by the Technical University of Gdansk (TUG), was used to measure the rolling resistance of the test sections. The TUG trailer was participating in the MIRIAM project where trailers for measuring rolling resistance were evaluated. The TUG trailer came out with a good repeatability and it is now the most used trailer in Europe for measuring rolling resistance. The trailer is equipped in such a way that influences from factors as road inclination and longitudinal acceleration are eliminated.

Three tires were adopted and compared for the measurement of the RR coefficients (Figure 26, Table 12). The SRTT ("Standard Reference Test Tire") is specified in ASTM F2393 as a reference tire for various purposes. The AAV4, light truck tire, is a tire tested and found to classify pavements (for noise) in roughly the same way as a selection of regular heavy truck tires do. The smallest dimension for this series of tires, SRTT, fits on large passenger cars. The MCEN tire was used by TUG from the time when they started to make RR measurements and has been kept for the purpose of providing a link to old measurements (Sandberg et al, 2011).

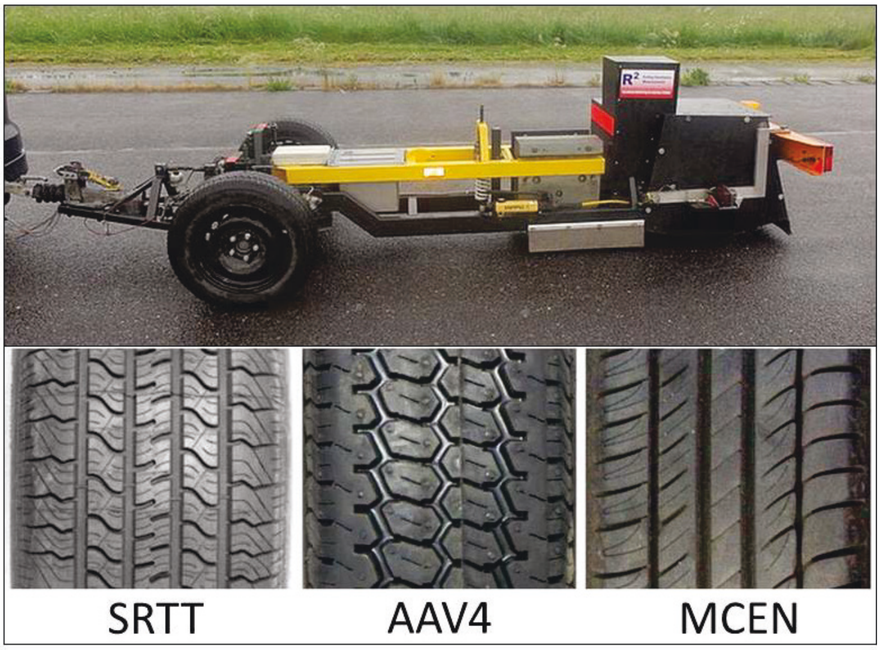


Figure 26 - The tire/road rolling resistance measurement TUG trailer and tires used.

Table 15 - Tires characteristics

Tire	SRTT	AAV4	MCEN
Size	225/60R16	195R14C	225/60R16
Construction	Tread: 1polyes-ter+2steel Sidewalls: 1polyester	Tread: 1ny-lon+2steel+2polyester Sidewalls: 2polyester	Tread: 1polyester + 2steel + 1polyamid Sidewall: 1polyes-ter
Max load [kG]	730	950/900	750
Max inflation [kPa]	240	450	350
Hardness [Sh]	65	62	63/70

It is relevant to recognize that the tires used in 2012 and 2013 have been also used on other test sections and these may present different levels of wear. The DRD bought their own tires which were used in 2014 and the following years.

Temperature Correction Factor

Temperature correction was applied following the ISO 28580 (*ISO 28580:2009*) (2):

$$\mathbf{C_{r,25} = C_{r,T} \cdot \{1 + K(T - T_{ref})\}} \quad (2)$$

Where $C_{r,25}$ is the Rolling Resistance coefficient at the Reference temperature;

$C_{r,T}$ is the Rolling Resistance at the measurement temperature;

K is constant related to the used tire. (K_{SRTT} = 0.015, K_{AAV4} = 0.010, K_{MCEN} = 0.015)

All RR coefficients represented below were corrected using the mentioned approach.
Furthermore, if the same load is applied on the measurement wheel then type and aging of the tire, used for rolling resistance measurements, might be relevant variables to control.

Rolling Resistance measurements

Rolling Resistance measurements were completed during week 30.
The research team from Technical University of Gdansk was able to measure different sections paved with low rolling resistance pavements. RR measurements campaign included:

- M14 on KVS;
- M30 on SMA11 and KVS;
- 119 on KVS;
- M60 on KVS;
- Vej 619 on KVS paved in 2012;
- Vej 619 on KVS paved in 2015.

The results from the test section paved in 2012 are not presented because the measurements did not show RR difference between the Low Rolling Resistance and standard SMA8. This pavement was the first test section paved during the COOEE project and was not produced applying the mix design optimization developed during ROSE project.
The figures (Figure 27, Figure 28, Figure 29) below represent the RR measurements (with SRTT) performed in 2018 and 2019. Rolling resistance reductions shown in the charts are referred to a standard pavement type paved in close proximity to the test section.

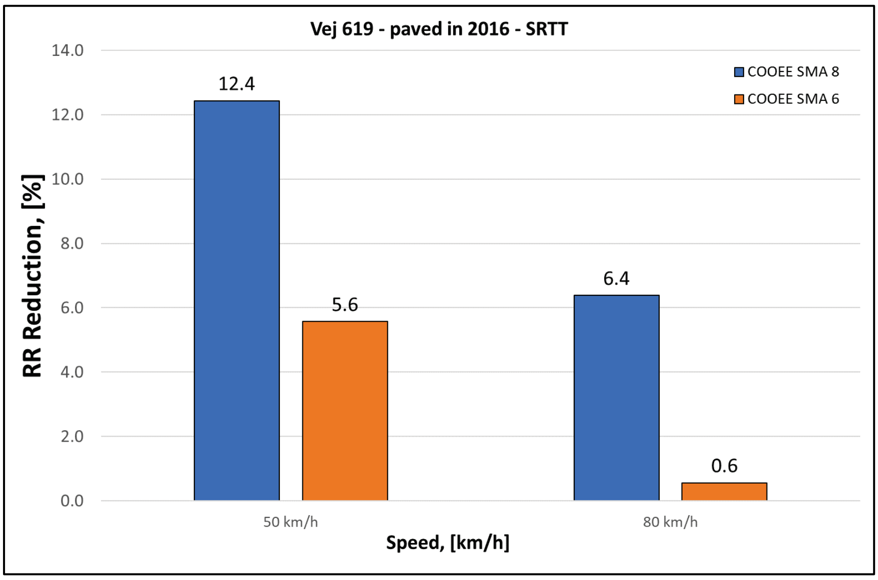


Figure 27 - RR reduction compared to SMA8 standard – 50 and 80 km/h

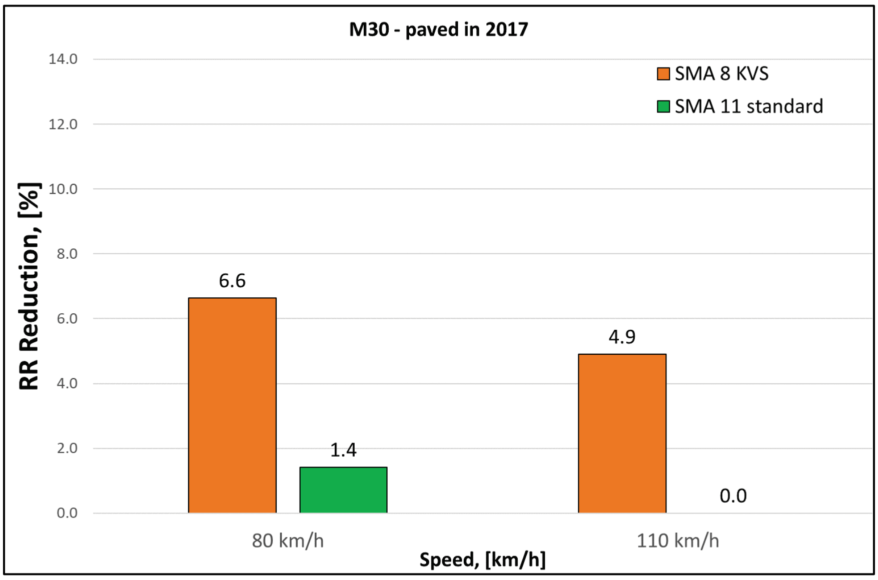


Figure 28 - RR reduction compared to SMA11 standard – 80 and 110 km/h

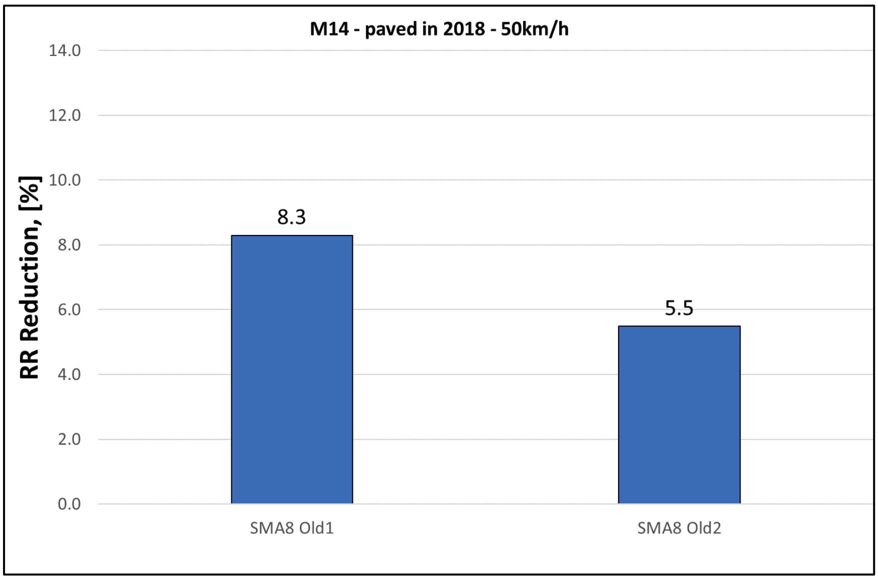


Figure 29 - RR reduction compared to SMA8 standard – 50km/h

Based on the RR data visualized in the figures, the following aspects can be highlighted:

- RR reduction reduces with increase in speed. KVS is more effective at low speed. At 110 km/h, the difference between KVS mixture and SMA11 is about 5% while at 80 km/h goes up to 6.6%;
- The highest contribution, in terms of RR reduction was measured at 50 km/h. This analysis was done on two test sections and the RR reduction was on average 9.2% (compared to a SMA 8). RR data measured on SMA11 at 50 km/h are not available.

To further understand the results, RR measurements have been averaged after being corrected to a reference temperature of 25°C. The temperature correction factor needs to be further validated but if applied over a set of data collected at similar temperature and over many measurements, the corrected RR value can be considered reliable.

Table 16 does summarize the RR measurements performed in 2018 and 2019. For each mix type, a RR value was calculated averaging the different measurements available at the same speed.

Table 16 - RR data from July 2018 and April 2019 corrected to a reference temperature and reductions.

Mix type	Rolling Resistance at 25°C []		RR reduction at 25°C [%]	
	80 km/h	110 km/h	80 km/h	110 km/h
SMA 11	0.00926	0.01046	Ref	Ref
SMA8 KVS	0.00856	0.00977	7.6	6.5
SMA8 st	0.00867	NA	6.4	NA

Fuel consumption measurements

The DRD has contracted a Dutch company “M+P” to measure fuel consumption (FC) on the KVS and standard sections. The equipment is presented in Figure 30.

Figure 30 - M+P fc measurement equipment

For the measurements, a 2016 Mercedes Vito 119 Bluetech (registration VT-341-Z) was used. It was fitted with Continental ContiVanContact 200 tires which were set at 3.3 bar at 10°C air temperature.

The fuel consumption is measured from the on-board computer in *L/hr*. This is determined from the quantity of fuel that is actually injected in each combustion cycle and multiplied by the number of combustions per revolution and the rpm.

Because the expected variations on the fuel consumption due to differences in road texture are typically small, it is critical to reduce influencing factors that are not being investigated in this project.

The following check list was used to reduce the unwanted influences:

- if possible, select measurement days with low wind speeds (< 5 m/s) and limit the amount of other traffic;
- weather conditions: dry, low wind speed, air temperature around 20°C;
- run-in of approximately 30 minutes. The tire pressure is monitored, and measurements were done only when the tire pressure was stable;
- the weight of the vehicle should be kept as constant as possible by keeping the tank full and driving with the same number of operators;
- keep measurement speed constant at 84 km/h;
- drive with cruise control in highest gear;

- external energy consumer should be kept constant;
- keep distance of at least 50 meters from traffic (front and back).

Because the FC measurement method is influenced by many different variables and that impact of pavement texture on FC is very difficult to isolate when data are collected over a singular section, the FC investigation was formulated with the main objective to define an empirical model to estimate FC based on MPD which could be used as support to the MIRAVEC model (Carlson et al. 2013). For this purpose, FC measurements have been ordered over different types of pavements including most of the KVS sections paved in 2018. M14 was not included in the FC measurement campaign due to both amount of traffic normally present in that section and speed limit of 60 km/h.

A total of 200 km of FC data were collected. All processed data used in this investigation were measured by the same vehicle and averaged over 20 meters section length. Texture data and longitudinal profile data point, used in the regression analysis, are an average value of the relative measure on both wheel paths 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 speed on some sections was significantly higher than that used to calibrate the wind correction model. Strong wind was faced mainly on the M30. 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.

Texture laser data collected on the wheel paths have been used to measure several texture and profile characteristics including IRI and Mega-texture. Distribution of the measured texture and profile characteristics are shown Figure 31.

IRI data ranges 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 found to range from 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;
- IRI data set was too narrow and when included in the statistical analysis of the FC data, IRI was found not to be as significant as the MPD.

The result of the regression analysis shows that fuel consumption increases with the increase in texture depth (Figure 32). Reliability of the regression model is low (Multiple R = 0.4, R^2=0.17) but this is probably related to the fact that FC is affected by many different variables and those related to the surface characteristics have a relatively small impact when compared to others such as wind and slope of the road. Furthermore, FC measurement has as well some variability which might affect the robustness of the extracted model.

In general, it is relevant to highlight that the FC reductions calculated using the model in equation (3) does not differ significantly from those developed in the MIRAVEC project.

$$(3) \qquad FC = 0.1729\ x\ MPD + 4.1410$$

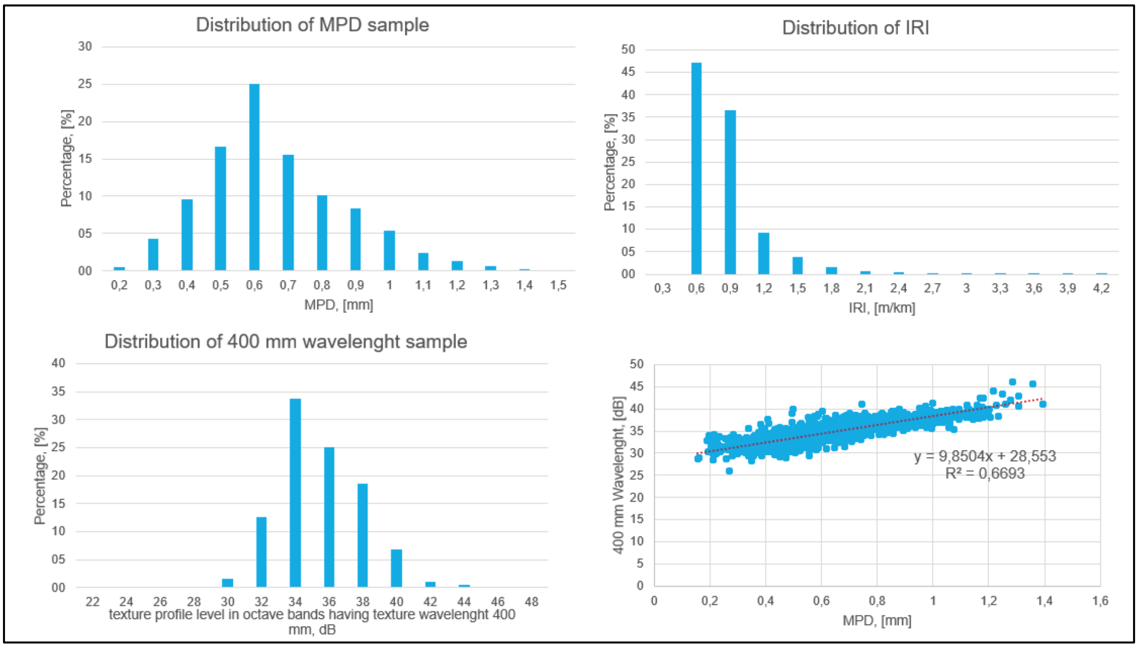


Figure 31 – Distribution of MPD, IRI and 400 mm wavelength samples on the pavements where FC measurements was completed

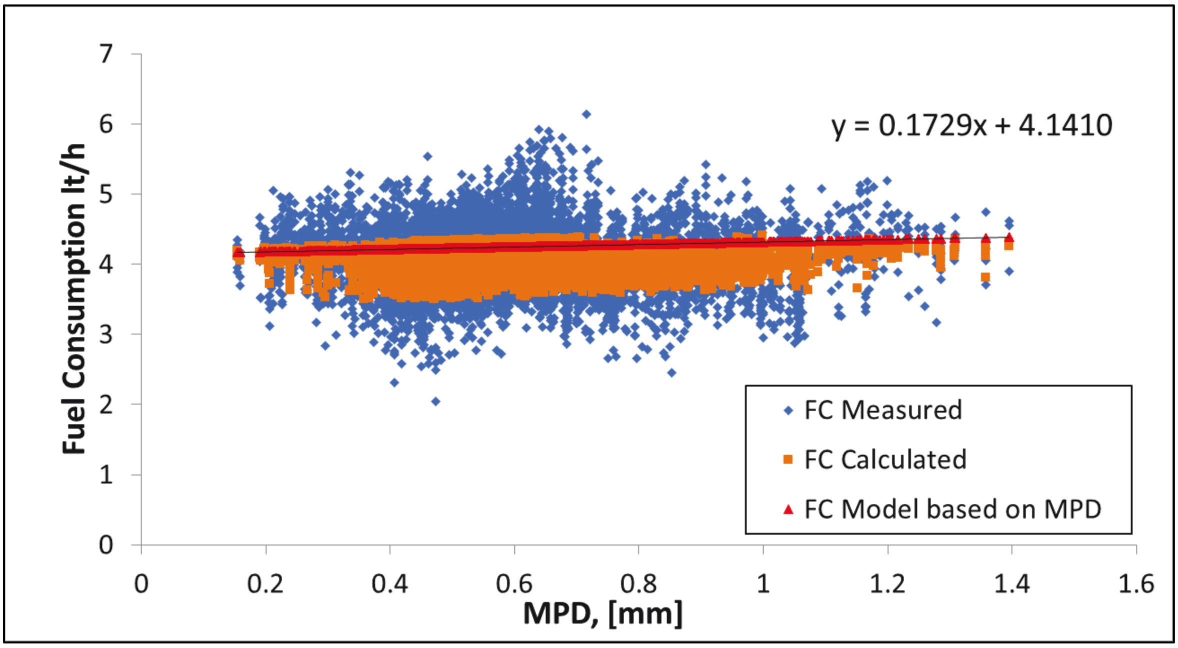


Figure 32 – FC regression model as function of MPD

The model represented in equation 3 was used to estimate hypothetical reduction of CO_2 which could be produced by the implementation of a Climate friendly pavement on DRD road network. This model cannot be considered reliable if applied on pavements having different roughness characteristics from those used to calibrate the model. The model has been calibrated on pavements having negative texture, so it is not known if the validity can be extended also to other pavement types. The model can be considered reliable for MPD values between 0.3 mm and 1.3 mm.

Potential for CO_2 reduction based on surface characteristics

The potential reduction by substituting the SMA wearing courses normally chosen for the Danish State Road Network with a KVS wearing course has been evaluated, based on the surface characteristics and relative development. Results obtained with the accelerated testing showed that the main advantage of the KVS is the longevity of the texture compared to the SMA wearing courses. The rolling resistance values measured by the TUG trailer could only be used to evaluate the initial fuel savings, but the development of rolling resistance during the wearing course life is yet unknown. To quantify the development of future fuel (and CO_2) savings, the model described in equation 3 of the present report was used and fed with data for MPD development of actual SMA wearing courses. Initial MPD and relative development for KVS was extracted from the results obtained at Ulster university using the Road Test Machine.

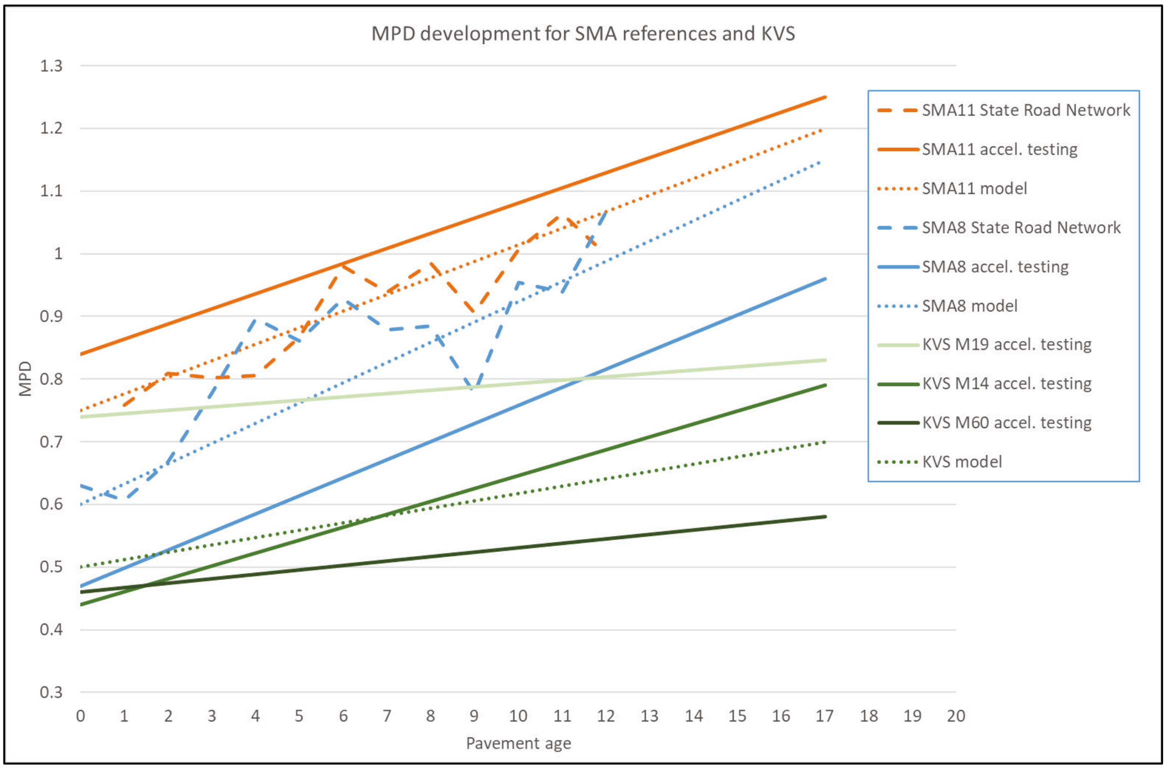


Figure 33 - Measured MPD developments and assumptions for developments used in the calculations.

The starting point in Figure 33 are MPD-values measured on the State Road Network for the two wearing course references SMA8 and SMA11, both showing an increasing trend with increased wearing course age. During the accelerated test, the pavements samples were subjected to 60.000 load applications. Relative shift factors, to covert number of wheels passes to life time, were calculated by comparing the changes in MPD of a standard pavement with those obtained at the RTM. The analysis has given a shift factor of 2.817E-4 years/wheel passes and consequently it was found that the testing could have been considered representative of a period of 17 years. The trend lines for the actual pavements and the accelerated testing are then reasonably parallel. The results from the accelerated testing of the KVS samples are also illustrated in the Figure 33. Finally, from these measured data, simplified model assumptions for the MPD development of SMA11, SMA8 and KVS are evaluated.

Table 17 - MPD values used in as basis for the calculation of potential CO_2 reduction.

	SMA11	SMA8	KVS
Initial MPD value	0.75	0.60	0.50
MPD after 17 years	1.20	1.15	0.70

Especially for KVS, where the accelerated testing gave rather varying results for the three different KVS sections, a solid estimation of MPD development is difficult, but the values have been chosen to reflect that the MPD development rate of KVS is lower than for the SMA references, which was the main result of the accelerated tests performed at both VTI and Ulster University.

With regards to fuel consumption (FC), the adopted model assumes 2.9% fuel consumption reduction when MPD is reduced from 1.25 mm to 0.5 mm.

The following methods and assumptions provide the basis for FC calculations and results:

- The potential reduction by using KVS is calculated relative to the wearing course that would otherwise be chosen. Currently this reference is SMA8 for the main roads and SMA11 for motorway sections where noise emission is not critical. However, since SMA8 is today used on a large proportion of the motorways (and especially those with high traffic volumes), SMA8 is considered the reference wearing course for 70% of the motorways and SMA11 for the remaining 30%.
- Fuel savings relative to the SMA references are time dependent and increasing with wearing course age.
- All wearing courses are substituted during a 15-year period, with 1/15 each year. The wearing courses paved in e.g. year 10, only contributes with savings for the following years, and the savings calculated represent the saving potential for the first years relative to the SMAs.
- A 17-year calculation period has been chosen since this is a conservative estimation of KVS wearing course life.
- The traffic volume for 2018 for main roads and motorways is used as starting point for the calculations and an annual traffic increase of 1,5% is applied.

- The CO_2 reduction potential is calculated based on a CO_2 emission of 180 g/km. This is an estimation for a weighted average value for cars and trucks representing the calculation period 2020 – 2037. In 2018 the corresponding value was 206 g/km, but this value will gradually decrease as a result of more strict emission requirements for new vehicles and an increasing proportion of electric vehicles.

With this model and an assumed linear MPD-increase, the following potential fuel and CO_2 reductions can be calculated (Table 18):

Year	Fuel reduction KVS ref. SMA11 (%)	Fuel reduction KVS ref. SMA8 (%)	Percentage wearing courses substituted	CO_2 reduction potential main roads (ton CO_2)	CO_2 reduction potential motorways (ton CO_2)	Total CO_2 reduction potential State Road Network (ton CO_2)
2020	1.01	0.41	7	362	1,335	1,697
2021	1.07	0.49	13	809	2,885	3,694
2022	1.13	0.57	20	1,346	4,657	6,004
2023	1.19	0.66	27	1,976	6,661	8,637
2024	1.24	0.74	33	2,702	8,905	11,607
2025	1.30	0.82	40	3,528	11,398	14,926
2026	1.36	0.90	47	4,458	14,149	18,607
2027	1.42	0.99	53	5,496	17,168	22,664
2028	1.48	1.07	60	6,646	20,465	27,111
2029	1.53	1.15	67	7,912	24,049	31,961
2030	1.59	1.23	73	9,298	27,931	37,229
2031	1.65	1.31	80	10,808	32,121	42,930
2032	1.70	1.39	87	12,448	36,631	49,079
2033	1.76	1.47	93	14,222	41,472	55,693
2034	1.82	1.55	100	16,133	46,654	62,787
2035	1.87	1.63	100	17,736	50,520	68,256
2036	1.93	1.71	100	19,380	54,484	73,864
2037	1.99	1.79	100	21,065	58,547	79,612
2021-2030				44,171	138,268	182,438
2020-2037				156,325	460,032	616,357

Table 18 - Potential fuel and CO_2 reduction for a gradual full implementation of KVS on the State Road Network.

Economic perspectives of paving KVS

Socio-economic analysis

Four KVS stretches were paved in 2018 as part of the large-scale implementation project where the Danish government, through the *PSO-aftalens grønne klimapulje*, funded the added price of the KVS. These stretches enabled comprehensive measuring campaigns to increase knowledge on the material- and functional properties and effects of KVS, as a pavement type, from large-scale implementation to allow for a final documentation of these.

KVS was paved on *Helsingørmotorvejen* (M14), *Østjyske motorvej* (M60), *Sydmotorvejen* (M30) and *Skovvejen* (route 119), all specified below (Table 19).

Table 19 - Specification of where KVS was paved in 2018

Location	Name	No	Length [km]	Side	From	To	Previous pavement type	Last paved
Distrikt Østdanmark	Helsingørmotorvejen	14	3	H	400994	410475	50SMA	1993
Distrikt Østdanmark	Helsingørmotorvejen	14	3	V	410000	410520	80SMA	1993
Distrikt Østdanmark	Sydmotorvejen	30	10	H	1370545	1440020	TBk	2001
Distrikt Østdanmark	Sydmotorvejen	30	11	V	1390495	1430400	80AB	2000
Distrikt Syddanmark	Østjyske Motorvej	60	4	H	900660	920252	80SMA	1994
Distrikt Østdanmark	Skovvejen	119	4	V	200700	220373	60SMA	2005

From the paving contracts, the price of KVS from each paved stretch was placed into an impartial analysis to obtain a future realistic price for KVS. Seeing that the paving of KVS in 2018 was a first KVS-contract for all but one of the involved contractors, it was strongly expected that a significant portion of the added price of KVS could be subscribed to the risk of working with KVS as a new pavement type. Through the impartial analysis, it was assessed that a realistic future price of KVS is 10 % higher than was is currently used as the standard pavement. For the further socioeconomic analyses, 10 % in added price for KVS is therefore employed as a fixed price.

Alongside having a specified added price of KVS as input for the socioeconomic analyses, results from measurements conducted on the four KVS-stretches on MPD, IRI, alongside updated values of noise annoyance and AADT as input allows for socioeconomic analyses on how the added price generates socioeconomic resource back to the society.

As a key objective for conducting socioeconomic analyses of KVS-implementation, the results can be used to analyze where on the Danish state road network the implementation of KVS can be focused most effectively. The four sections are included in the subsequent analyzes with the specific areas and specific driving directions on which KVS is paved.

The socio-economic analyzes result in four main outcomes; *net present value, internal interest rate, net profit per public invested krone*, as well as *CO_2 shadow price*.

The net present value reflects the total value of all costs and effects, discounted to 2019 with a discount rate (4%). A positive net present value means that the measure is profitable.

Internal rate is the discount rate, which gives a net present value of zero. An internal rate of more than 4% means that the measure is profitable.

Net profit per public invested krone compares the profit with the impact on the Treasury. Here too, a positive value entails that the measure is profitable. The note of lower fuel tax revenues, due to the lower rolling resistance, is included as a loss to the public coffers.

The CO_2 shadow price is an expression of the specific socioeconomic cost of KVS to reduce a single tonne of CO_2 equivalent. A negative shadow price (which results in a positive net present value) means that there will be socioeconomic surplus by implementing the measure, even without a CO_2 reduction. Thus, the CO_2 saving will by itself not entail a socioeconomic cost. The magnitude of a negative value in shadow price may be difficult to interpret.

To conduct the socioeconomic analyses, the company *Incentive* has developed a tool specifically tailored to analyse the benefits of paving KVS as opposed to other types of pavements, in socioeconomic terms. The tool is based on the TERESA (*Transportministeriets Regnearksmodel for Samfundsøkonomisk Analyse*) model. TERESA is specifically designed for socioeconomic analyses within the field of transportation (Incentive, 2013).

Incentive has as key merit in this context and project to have been the key developer of TERESA which hereby secures the integrity of the tool developed for socioeconomic analyses on KVS-implementation. This developed tool was made in accordance with ruling principles of socioeconomic analyses marked by the Danish Ministry of Finance. By employing this TERESA-based tool, the socioeconomic results in this project is in line with already existing, proven and accepted approaches from other Danish ministries which enables direct basis for comparing effects and perspectives across sectors and initiatives of CO_2-reduction.

As written above, KVS is assessed to have an added price of 10 %, compared to other pavements currently opted for. This added price forms the basis of the socioeconomic analyses where the added price is compared to monetized beneficial effects. All socioeconomic analyses are conducted by comparing how paving KVS will affect the society as opposed to a pavement type currently otherwise used. The socioeconomic analyses are calculated over 16 years, corresponding to a conservative assumption that the lifetime of the KVS is equal to the lifespan of another pavement type otherwise used. If the expected additional lifespan of KVS is achieved, for example 1-3 years, it will result in better socioeconomic results.

Input parameters for the socioeconomic analyses are as follows:

- Pavement costs, both KVS and a pavement type currently used (10 % added price for KVS)
- Lifespan, both for KVS and a pavement type currently used
- Noise annoyance number, including development throughout lifespan (modelled)
- Urban proximity specification which will enable inclusion on effects of particle pollution
- Fuel consumption for KVS and pavement types currently used (SMA8 & SMA11), as specified in "Potential for CO_2 reduction"
- AADT, including assumed development throughout lifespan, equal assumption as used in the CO_2-reduction potential later described in this report.

As shown in Table 20, KVS is analysed as profitable on all paved stretches. On two of these sections, the extra cost has been earned back to the society in less than a year, so it is a very good socio-economic investment. In general, it is saved driving costs for road users which provides the greatest contribution to the positive effects. In addition, noise reduction generates a particularly high gain on the M14, as the traffic load (AADT) is the highest of the four stretches and the road stretch is heavily situated in urban areas. The most significant negative effect is generally lost fuel taxes to the state, where additional investment weighs less heavily.

Table 20 - Summary of socio-economic results of the four sections with KVS and a specification of the average CO_2 reduction per year per section over the lifetime

Present day values in mill. Kroner	Helsingørmotorvejen (M14)	Sydmotor-vejen (M30)	Østjyske Motorvej (M60)	Skovvejen (Route 119)
Operation (marked price) – added costs.	-1,0	-1,0	-0,2	-0,2
Driving costs	28,3	10,2	4,4	1,5
Noise	12,1	0,7	0,0	0,0
Air pollution	2,2	0,7	0,3	0,1
Climate/CO_2	2,3	0,8	0,4	0,1
Tax charges (incl. corrections)	-10,6	-3,8	-1,7	-0,6
Labour supply	0,7	0,2	0,1	0,0
Net present value	33,9	7,7	3,4	1,0
Internal rate is the discount rate	>100%	80%	>100%	63%
Net profit per public invested krone	2,91	1,58	1,86	1,39
CO_2-reduction (avg. tonne annually)	525	189	82	28
CO_2-shadow price (kroner per tonne)	-4.022	-2.432	-2.466	-2.186

The operation must be read as both costs for construction and operation of KVS and is translated at market prices in TERESA. In short, here the public spending (and revenue) is compared with private consumption, incl. VAT and taxes. Driving costs, in this regard, consist of fuel consumption.
As shown in Table 20, KVS is profitable on all lines. On all the paved KVS-stretches, the socioeconomic investment is proven successful.
As mentioned, it is saved driving costs for road users, which makes the greatest contribution to the positive effects. In addition, the noise-reduction effect on M14 provides a particularly high socioeconomic gain. Again, the most significant negative effect is generally the lost fuel taxes to the state, where additional investment is less significant.

Economic implementation analyses

Theoretical socio-economic calculations have also been carried out for roads similar to route 119, but with lower traffic as most effects follow the traffic volume. It is not possible to give a general indication of the noise effect in this context, so this is omitted. These theoretical analyzes have been carried out to identify the level at which KVS can be applied profitably. Seeing the profitability is heavily influenced on AADT, the theoretical are based with this as criteria. The results are shown in Table 21.

Table 21 - Overview of the profitability of paving KVS, based on criteria with varied traffic volume (ÅDT)

Present day values in mill. Kroner	> 6,000 in AADT	2,200 in AADT
Operation (marked price) – added costs.	-0,2	-0,2
Driving costs	0,6	0,2
Noise	Not incl.	Not incl.
Air pollution	0,0	0,0
Climate/CO_2	0,1	0,0
Tax charges (incl. corrections)	-0,2	-0,1
Labour supply	0,0	0,0
Net present value	0,3	0,0
Internal rate is the discount rate	23%	4,2%
Net profit per public invested krone	0,74	0,01
CO_2-reduction (avg. tonne annually)	12	5
CO_2-shadow price (kroner per tonne)	-1.468	240

As evident in Table 22, KVS is profitable on state roads with traffic loads on road with an ADT of approximately 2,000 or more. Approximately 95% of the state roads have an AADT of 2,000 and above. Thus, it is assessed that KVS is socioeconomically viable on the vast majority of the state road network.

A transition to opting for KVS as the sole future pavement type will result in an annual additional cost of around DKK 26.4 mill. seen for the period 2020-2029, based on an added price of 10% for KVS. The defined annual need varies according to the resource need specific for the respective year for the natural re-paving cycle on the state road network. At present, an annual variation of the additional cost to KVS is seen between DKK 9.6 - 43.0 mill. kroner during this period (2020-2029) and is specified in Table 22 below.

Table 22 - Overview of the Road Directorate's needs assessment for pavement replacement, distributed on an annual basis over the period 2020-2029, and an estimate of what KVS will comprise of additional costs in choosing this pavement.

Year	Ressource needs (mio. kr.)	Added cost for KVS (mio. kr.)
2020	137	13,7
2021	204	20,4
2022	300	30,0
2023	430	43,0
2024	246	24,6
2025	370	37,0
2026	393	39,3
2027	273	27,3
2028	192	19,2
2029	96	9,6
Total	**2.641**	**264,1**

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Conclusions

Four different contractors were involved in the demonstration project on Climate friendly asphalt. The list of paved test sections and the relative contractors is summarized in Table 1.

Only the section paved by NCC was defined based on a standard tendering process. An additional Climate friendly pavement was negotiated with NCC on Nordjyske Motorway, but due to some issues faced during the trial production, the Danish Road Directorate has decided to pave a standard SMA11 in accordance to what was originally defined within the terms of the contract (before the planning of Climate friendly asphalt).

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, Munck has produced the mix with the highest percentage of passing to the 2 mm sieve. This resulted into a very low MPD and a friction level close to the acceptable limit. Colas, instead has adopted a different strategy during production and kept that percentage closer to the lower limit of the envelope. The result was a higher texture depth, which also meant that the friction demands were fulfilled within a shorter period.

With regards to friction: Standard friction development cannot be applied on KVS mix types. This is because it is produced with a high content of high polymer modified bitumen and fine gradation. The following remarks need to be accepted if DRD wants to proceed with the implementation of KVS mixture on a network level:

- The thicker coating of the mortar makes this mix type more slippery at the beginning compared to standard SMA8 or SMA11.
- The rate of which friction develops to a stable level is longer comparable to standard SMA8 and SMA11.
- Stability of the friction measurements are affected by the above-mentioned mix properties. This means that it will take longer time before the friction can be measured evenly on the pavement in the longitudinal direction.
- KVS mixture paved by Colas on the Hldv 119 is an exception simply because the produced mix has a lower content of fines and bitumen, which gave higher MPD. Basically, their mix type is closer to an SMA8 standard and this is the reason why the MPD is approx. 0.7 mm.

DRD has decided to include an additional test to study the durability of the textures on specimens sampled from the 6 different sections.

- SMA11 Reference (M14)
- SMA8 Reference (M14)
- SMA8 SRS (M40)
- SMA8 KVS (M14)
- SMA8 KVS (Hldv 119)
- SMA8 KVS (M60)

The test was performed at Ulster University and the results have shown that KVS mixtures have a durable and stable texture. Optimized selection of aggregates, high content of polymer modified binder combined with the use of selected fillers provides a longer durability of the KVS mixture compared to a standard SMA8. The expected durability of the KVS should be approximately similar to a standard SMA11 (average 17 years). The KVS mix has a very high cracking and permanent deformation resistance. DRD could consider applying these mix design adjustments on standard SMA8 - increasing the durability up to 2 - 3 years.

Within the KVS project, DRD has been working on the development of a method to estimate the quality of the paving operations which could be used to identify pavement areas where it is expected to have poor degree of compaction and consequently premature failures. All the paved sections were monitored during construction and IR data were collected.
To improve a guarantee of high quality of paving operations, also friction measurements appear to be relevant when friction on left and right wheel path are compared.

Functional properties have been summarised in Table 13. The difference in MPD between the different contractors are related to difference in production and adopted mix design. In fact, the mix specifications allow a contractor to define a gradation within a relatively open envelope. The difference between minimum and maximum limits for each sieve are defined based on European Standards. In this specific case, MUNCK and YIT have produced a finer mixture and the percentage of passing of the 2 and 4 mm sieves is close to the upper side of the envelope. Colas has produced a coarser gradation which follows the lower side of the envelope.

Noise measurements show that KVS mix have noise absorption like a standard SMA8. Based on the analysis of the noise spectra, it is not possible to predict how KVS noise emissions will develop over time. Due to the enhanced texture stability and durability, noise emissions of KVS pavements are expected to have a lower growing rate than standard mix and SRS mixtures.

KVS pavement type has low RR properties compared to standard SMA8 and SMA11. On average, KVS has showed 7% RR reduction during the measurement campaign completed in April 2019.

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Using FC measurements, it was possible to extrapolate a linear model that correlates texture depth and Fuel consumption. Using the developed model, expected FC reductions compared to standard pavements over life time were calculated (Table 23):

Table 23 – calculated CO_2 reductions given by KVS pavement

CO_2 reduction [%]	Pavement age (years)	
	0	17*
KVS vs SMA11	1.00%	2.00%
KVS vs SMA8	0.40%	1.80%

* expected life time of KVS pavements

CO_2 reductions given by KVS, when compared to standard pavements having the same age, are expected to increase over time due to the long-lasting performance and texture stability.
If KVS pavement is implemented in Denmark starting from 2020, the amounts of expected CO_2 reduction are shown in Table 24.

Table 24 Potential fuel and CO_2 reductions given by KVS implementation

Year	CO_2 reduction potential main roads (ton CO_2)	CO_2 reduction potential motorways (ton CO_2)	Total CO_2 reduction potential State Road Network (ton CO_2)
2021-2030	44,171	138,268	182,438
2020-2037	156,325	460,032	616,357

The additional price of the KVS mixture has also been investigated. Also, Deloitte has investigated what the price development would be if the usage of the mix were to be applied on a bigger scale. The report of Deloitte is attached as an appendix in Danish.

DRD has organized workshops with the different contractors to understand their experiences with the KVS mixture and to receive direct information about challenges and possible improvements.

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Further economic perspectives have been analysed to place the added price of KVS into both socioeconomical analyses and into how the added price can contribute to a specific CO_2-reduction related to which stretch(es) KVS is paved.

In the context of socioeconomic analyses, KVS proved to be beneficial, seen from a socioeconomic viewpoint, regardless of which of the four stretches was analysed. Generally, the higher the daily traffic load, the more beneficial the socioeconomic results. Both in terms of return of investment for the added price of KVS and KVS' economic ability as a mean to reduce CO_2 (given through the results of shadow price), KVS is proved beneficial to fund, also as an initiative to reduce CO_2.

Three scenarios are given to illustrate different approaches of identifying specific economic optimums to determine the rate and degree of paving KVS. Through these scenarios, the price (in DKK) to reduce CO_2 (tons) ranged from 319 to 9,490. These numbers clearly illustrate that KVS can be paved more economically beneficial at stretches with high figures of daily traffic loads. However, the highest degree of CO_2-reduction is naturally linked to a higher degree as KVS paved, meaning the more KVS is used as the pavement of choice, regardless of traffic load, the higher the CO_2-reduction.

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Annex A Description of requirements (intended goal) for the asphalt material for the demonstration trials

The mix design for the rolling resistance optimised surface layer which has been developed and tried during previous projects (COOEE, COOEE+, INNO-ENERGI I & II) has been converted into a frame work for the specification for a variant of stone mastic asphalt in order to allow various contractors to further develop their candidate of climate friendly surface layer. The requirements were intended to follow as close as possible the requirements in accordance with the European product standard for stone mastic asphalt, DS/EN 13108-5:2016 and fulfilling the Construction Product Legislation for CE-marking. It was for these implementation trials necessary to have additional specifications because the European product standard lacked possibilities to define certain important features. The most important ones were the requirements for the bituminous mortar consisting of a polymer modified bitumen (40/100-75 in accordance with DS/EN 14023:2010) in combination with specific mix requirements (5.9 % added limestone filler and 1.5 % of hydrated lime with respect to the total aggregate part of the mix).

The document of the requirements (in Danish) can be found on the following pages as it was presented to the contractors for the three demonstration trials KLIVE18#01., KLIVE18#02 and KLIVE18#03.

One of the contractors was allowed to replace the 1.5 % of hydrated lime with 1.5 % additional limestone filler + addition of 0.3 % of adhesion improving agent (TAS) after demonstrating that this change would not have an impact on the moisture sensitivity of the material and fulfilling the functional requirement.

Vejdirektoratet

Vejdirektoratet

Dato	14. februar 2018
Sagsbehandler	Erik Nielsen
Mail	enie@vd.dk
Telefon	
Dokument	DokNr
Side	1/3

Specifikationskrav til asfalt (KLIVEJBEL) til forhandling efter udbud 2018

Materiale-ønsker og specifikationskrav

På baggrund af de seneste års forskning med udvikling af klimavenlig asfalt er der fundet et antal optimale værdier for det belægningsmateriale, som har indgået i tidligere forsøg. Notatet oplister en "oversættelse" af disse parametre til så vidt muligt generiske krav i henhold til produktstandard for SMA version 2016 inkl. supplerende krav afledt af den udførte forskning og udvikling, hvor gældende standard er utilstrækkelig. Tal i firkantparentes antyder fundne værdier for den pågældende parameter.

Specifikationskrav ved forhandling efter udbud

Generisk asfalttype

Produktstandard reference: DS/EN 13108-5 Skærvemastiks version 2016
Nominel Maximum Aggregate Size: 8 mm => SMA 8

Stenmateriale

Stenmaterialet udgøres af helknust klippemateriale i henhold til EN 13043

Intet krav til stendensitet, ρ.

Korrektioner af minimum-bindemiddelindhold i forhold til specifikt anvendt stenmateriale skal ske i forhold til en reference-stendensitet på 2,65 Mg/m^3. Se senere under bindemiddel.

Hulrum i stenmateriale: VMA_{min} = 18 % [18,1 %]

Specificeret kornkurve, samt ønsket Target-kornkurve (med kornkurve-tolerancer efter Tabel A.1 og A.2 i DS/EN 13108-21:2016):

Kornkurve (gennemfald) :

Sigtestørrelse	Specificeret kornkurvekrav	EN 13108-5:2016	Ønsket target-kornkurve	Tolerancer Tabel A.1	Tolerancer Tabel A.2
11,2 mm	100	1,4 D (Table 1)	[100 %]		
8 mm	90 – 100	D (Table 1)	[93 %]	-8 % / + 5 %	± 4 %
5,6 mm	56 - 66	(Table 3)	[61 %]	± 7 %	± 4 %
4 mm	41 - 51	(Table 3)	[46 %]	± 7 %	± 4 %
2 mm	28 – 34	(Table 3)	[31 %]	± 6 %	± 3 %
1 mm					
0,5 mm	15 - 19	(Table 3)	[17 %]	± 4 %	± 2 %
0,25 mm					
0,125 mm					
0,063 mm §)	8,4 – 10,4	(Table 3)	[9,4 %] [Max. 10,5 %]	± 2 %	± 1 %

§) Se vigtig oplysning næste side vedrørende fillerkrav

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Transport-, Bygnings- og Boligministeriet

Vigtig oplysning vedrørende kravene til filler fra eksisterende viden:

9,4 % er target-værdien, men 10,5 % er en absolut maksimalværdi for at fastholde friktion, tekstur, holdbarhed m.m. Når tolerancen er ± 2 %, ville det være vildledende at justere target-værdien ned til 8,5 %.

Specifikke materialetilsætninger, som beregningsmæssigt antages at indgå i stenmaterialet:

Kalkfiller	5,9 % (baseret på, at alt stenmateriale er 100 %)
Hydratkalk som klæbeaktiv filler:	1,5 % (baseret på, at alt stenmateriale er 100 %)
Cellulosefibre:	Det er frivilligt om cellulosefibre benyttes i recepten. Hvis den benyttes, skal det være ca. 0,35 % og regnes som indgående i stensammensætningen. (baseret på, at alt stenmateriale er 100 %).

Materialets mørtel og dens egenskaberne er en kritisk faktor, hvor fillermaterialets kornstørrelsesfordeling er en vigtig parameter og dermed bidrager til definition af materialetypen: Derfor gælder følgende:

- Kalkfiller kan ikke erstattes af kulflyveaske og
- Hydratkalk kan ikke erstattes af portland cement

Bindemiddel

Generisk type: 40/100-75

Type: Forud fremstillet polymermodificeret bitumen med elastomer med fuld specifikation i henhold til DS/EN 14023 (Vejregel for bindemiddel og klæbemiddel , side 5, elastomer)

Blødhedspunkt kugle og ring:	> 75 °C
Elastisk tilbagegang @ 200 mm og 10 °C	≥ 75 %
Elastisk tilbagegang (efter RTFOT):	Leverandørens Specificerede Værdi (LSV)

Asfalt (volumetriske krav)

Bindemiddel indhold	7,1 % (baseret på, at asfalt er 100 %) med en produktionstolerance på ± 0,5 %

Hvis der benyttes en klippemateriale med en anden stendensitet, ρ, end 2,65 Mg/m^3 , så korrigeres bindemiddelindholdet med følgende faktor α:

$$\alpha = 2{,}650 / \rho$$

Marshall DS/EN 12697-30 (2 x 50 slag):

- Hulrumsprocent (i henhold til DS/EN 12697-5): 1,5 – 4,5 %
- Bitumenfyldning (i henhold til DS/EN 12697-5): 80 – 92 %
- Tolerancekrav til VL (i henhold til DS/EN 12697-5) ≤ 7,5 %

Følgende ønskes oplyst:

- Forholdet Vb/Vs [0,204]
- Hulrumsprocent af gyrator-komprimeret prøvelegeme i henhold til DS/EN 12697-31 som funktion af antal gyrationer fra 0 til 200 gyrationer.

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Asfalt (funktionskrav eller krav i henhold til DS/EN 13108-5 og DS/EN 13108-21):		

Vandfølsomhed

- DS/EN 12697-12 @ 72 timer ved 40 °C: ITSRmin ≥ 80 %

Sporkøringsfølsomhed:

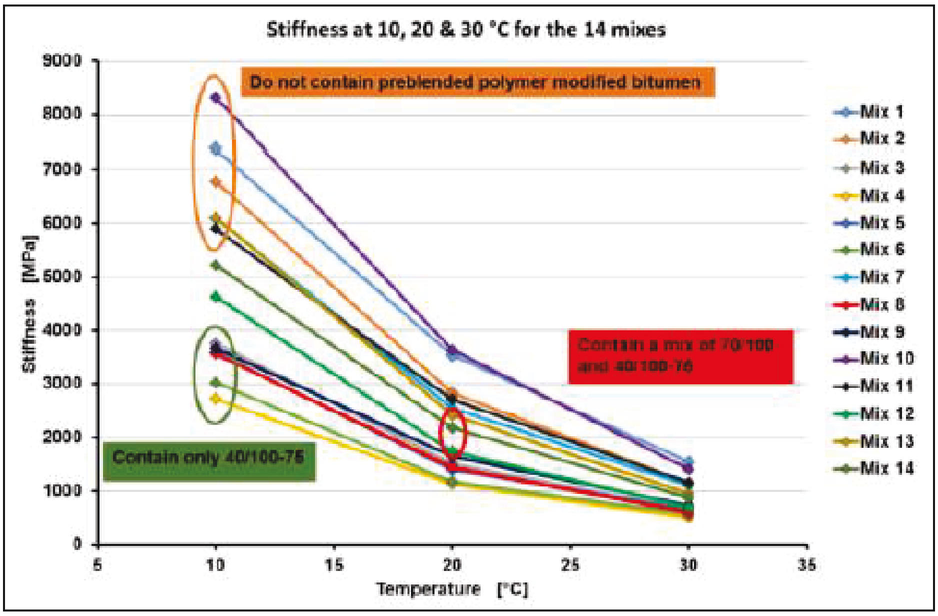
- Wheel Tracking test DS/EN 12697-22 @ (60 °C, 40 mm): WTS_{AIR} ≤ 0,04 mm/1000 cycles
- PRD_{AIR} ≤ 5,0 %
- (Alternativt RD_{AIR} ≤ 2,0 mm)

Bæreevne, stivhed:

- Stivhedsmodul DS/EN 12697-26 Max. stivhed @ 10 °C 5.000 MPa *)
- Min. stivhed @ 10 °C 3.000 MPa

---

*) Den laveste kategori, der findes for Smax i henhold til DS/EN 13108-5:2016 er 7.000 MPa, men det er for høj en værdi for at sikre, at der bliver anvendt en højpolymermodificeret bitumen med en blød basisbitumen. Se figur nedenfor (*Figur 17 fra InnoEnergi 2016 rapport, dateret 19. januar 2017*).



Hvis kravet til S_{max} ikke kan accepteres, må der som alternativ stilles krav til udmattelsesegenskaber af asfalten på følgende måde

Udmattelsesegenskaber:

Udmattelses DS/EN 12697-26 @ (4 punkt bøjning ved 10 °C):

- $\varepsilon_{6\ min}$ ≥ 90 microstrain

3

Annex B Requirements in tendering document for motorway M30 (Entreprise 79)

Below the requirements for climate friendly surface layer in the tendering document for motorway M30 is inserted. There is a correction in Danish text in paragraph 2.2.0: Twice , change “asfaltmix” to read “stenmaterialet”.

Vejdirektoratet

Særlige arbejdsbeskrivelser - Teknik (SAB-TEK)

Udbud af asfaltarbejder 2018 XVII

Vedligehold (VED) og Belægningsarbejder (VED-BEL)

JULI 2018

ENTREPRISE 79:
M30, km 137,545 – 144,020 h.s., inkl. 1 rampespids og
km 139,495 - 143,400 h.s., inkl. 2 ramper, ved Maribo

ENTREPRISE 82:
Hldv. 407, km 53,050 - 54,978, ved Sønder Rind

ENTREPRISE 84:
Hldv. 325, km 21,099 – 27,856, ved Gram

ENTREPRISE 86:
Hldv. 109, km 39,001 – 39,078 (rundkørsel + ben), ved Nyrup

Transport-, Bygnings- og Boligministeriet

Vejdirektoratet

SÆRLIGE ARBEJDSBESKRIVELSER FOR KLIMAVENLIGE ASFALTSLIDLAG

Supplerende bestemmelser til AAB – Varmblandet asfalt, februar 2012.

1. Alment

Denne særlige arbejdsbeskrivelse omfatter klimavenlig asfaltslidlag af typen SMA 8 KVS.

Hvor intet andet er anført, gælder de i AAB anførte krav for SMA 8, for klimavenlig asfaltslidlag af typen SMA 8 KVS.

1.1 Entreprenørens ydelser

Arbejdet omfatter udførelse af bituminøse belægninger jf. den aktuelle bestilling.

Entreprise 79, M30 ved Maribo
M30, km 137,545 – 144,020 h.s., inkl. 1 rampespids, og km 139,495 – 143,400 v.s., inkl. 2 ramper.
ÅDT pr. spor: 4.400, Æ10 pr. spor: 2.000

Eksisterende slidlag affræses, hvorefter der udføres:

Udskiftninger med ABB 11 eller ABB 16
Opretning/afretning med AB 6t eller AB 8t
70 kg/m² SMA 8
70 kg/m² SMA 8 KVS med PMB

Entreprenøren skal foreskrive og dokumentere den tilbudte asfalt ved sin ydeevnedeklaration.

Anvendes der genbrug i SMA 8 KVS, skal entreprenøren fremlægge identifikation og deklaration af egenskaber, for den anvendte genbrug jf. afsnit 1.4.

Entreprenøren skal fremlægge identifikation og deklaration af egenskaber, for det anvendte bindemiddel jf. afsnit 2.1.1.

Krav i afsnit 1.1 vedr. etablering og vedligehold af afmærkning og afspærring i AAB udgår, og erstattes af krav jf. afsnit 4 i særlig arbejdsbeskrivelse for arbejdsplads.

På de entrepriser, hvor bygherren ønsker at udføre forudgående reparation af revner, skal dette ske efter bygherrens anvisning.

1.2 Underlag

Underlaget vil være den eksisterende belægning på tilbudsdagen. Bygherren kan dog inden arbejdets udførelse foretage reparationer af den eksisterende belægning.

1.3 Krav til specifikationer og kontrol efter entreprisestørrelse

Arbejde med SMA 8 KVS henhører under entreprisestørrelse II.

Henvisning til afsnit 2.2.3 vedr. krav til specifikationer i AAB fastholdes.

1.4 Genbrug

Der kan anvendes genbrug i SMA 8 KVS iht. DS/EN 13108-5:2016.

Anvendes der genbrug i SMA 8 KVS skal genbrug skal være i overensstemmelse med DS/EN 13108-8:2016.

Krav til stenmaterialer i SMA 8 KVS jf. afsnit 2.1 omfatter også den del af stenmaterialet, der kommer fra genbrug.

1.5 Funktionskrav

De i særlige arbejdsbeskrivelser (SAB-TEK) for varmblandet asfalt anførte krav er gældende.

2. Materialer

2.1 Råmaterialer

2.1.1 Bindemidler og klæbemidler

Afsnit 2.1.1 i AAB udgår.

Som bindemiddel i SMA 8 KVS anvendes en PMB 40/100-75 iht. DS/EN 14023, idet bindemidlet skal overholde følgende krav:

- Penetration ved 25 °C: 40-100 x 0,1 mm (klasse 5)
- Blødhedspunkt k&r: ≥ 75 °C (klasse 3)
- Masseændring efter RTFOT: ≤ 0,5 % (klasse 3)
- Flammepunkt: ≥ 220 °C (klasse 4)
- Brudpunkt Fraass: ≤ -15 °C (klasse 7)
- Elastisk tilbagegang ved 200 mm og 10 °C: ≥ 75 % (klasse 2)
- Ændring af blødhedspunkt k&r efter RTFOT: ≤ 12 °C
- Elastisk tilbagegang ved 200 mm og 10 °C efter RTFOT: TBR (klasse 1)
- Forskel i blødhedspunkt k&r efter tubetest, ≤ 5 °C (klasse 2)

Som klæbemiddel anvendes type:

- Bitumenemulsion og modificeret bitumenemulsion iht. DS/EN 13808

Detailvalg af klæbemiddel påhviler alene entreprenøren.

2.1.2 Stenmaterialer

Afsnit 2.1.2 i AAB udgår.

Som stenmateriale i SMA 8 KVS, herunder bidrag fra genbrug, anvendes naturlige stenmaterialer iht. DS/EN 13043, idet stenmaterialet skal overholde følgende krav:

- Til grovfraktionen (≥ 2 mm), bortset fra lyst tilslag, skal anvendes klippemateriale

Som tilført filler i SMA 8 KVS anvendes kalk og hydratkalk iht. DS/EN 13043.

2.1.3 Additiver

Som additiver anvendes:

- Kemiske, organiske eller uorganiske materialer, i små mængder, jf. DS/EN 13108-5, af 2016

Detailvalg af additiver, og mængde af additiver, påhviler alene entreprenøren.

2.2 Varmblandede asfaltmaterialer

2.2.0 Generelle krav

Krav vedrørende bitumenhårdhed og Marshallkriterier jf. AAB udgår.

For SMA 8 KVS, reference DS/EN 13108-5:2016, gælder følgende:

- Maksimal kornstørrelse (D): 8 mm
- Gennemfald i %, 11,2-mm sigte: 100 %
- Gennemfald i %, 8-mm sigte: 90 – 100 %
- Gennemfald i %, 5,6-mm sigte: 56 – 66 %
- Gennemfald i %, 4-mm sigte: 41 – 51 %
- Gennemfald i %, 2-mm sigte: 28 – 34 %
- Gennemfald i %, 0,5-mm sigte: 15 – 19 %
- Gennemfald i %, 0,063-mm sigte: 8,4 – 10,4 %
- Min. specificeret bindemiddelindhold [B_{min}]: 7,1 %
- Specificeret indhold af tilført kalkfiller: 5,9 vægt-% af asfaltmix
- Specificeret indhold af tilført hydratkalkfiller: 1,5 vægt-% af asfaltmix
- Hulrum [V_{min} - V_{max}]: 1,5 – 4,5 %
- Bitumenfyldning [VFB_{min} - VFB_{max}]: 80 – 92 %
- Hulrum i stenmaterialet [VMA_{min}]: ≥ 18 %
- Følsomhed over for vand [$ITRS_{min}$]: ≥ 80 % ved 2 x 35 slag og 15° C, ref. DS/EN 12697-12:2018
- Permanent deformation [WTS_{AIRmax}]: ≤ 0,04 mm/10^3 cykler ved ved 60°C, 40 mm og komprimering ≥ 99 %
- Permanent deformation [PRD_{AIRmax}]: ≤ 5,0 % ved ved 60°C, 40 mm og komprimering ≥ 99 %
- Stivhed [S_{min} - S_{max}]: 1.500 – 5.000 MPa ved IT-CY, 10°C og 124 ms

- Indbygget hulrumsprocent [V_L], tolerance: ≤ 7,5 %
- Komprimeringsgrad [K], tolerance: ≥ 95,0 %, ref. DS/EN 12697-6, metode B

2.2.3 Specifikation for entreprisestørrelse II

Krav vedrørende specifikation jf. AAB fastholdes, idet krav om specifikation af Marshall-kriterier jf. AAB udgår.

2.3 Det færdige resultat

Den leverede asfalt skal overholde deklareringerne i entreprenørens ydeevnedeklaration.

3. Udførelse

De i særlige arbejdsbeskrivelser (SAB-TEK) for varmblandet asfalt anførte krav er gældende.

4. Kontrol

4.1 Alment

Entreprenøren skal dagligt og for hver belægningstype udfylde sammenhørende skemaer vedrørende udlagte mængder og entreprenørkontrol. Principper for Skemaerne findes i Tilsynshåndbog for asfaltarbejder.

4.2 Dokumentation af kontrol

Entreprenørens skal udtage og udlevere repræsentative prøver af råmaterialer, genbrug og færdig asfaltmix til bygherren, idet omfang af udtagning og udlevering af prøver aftales med bygherren forud for arbejdets opstart.

Såfremt bygherrens laboratorium foretager stikprøvekontrol under udlægningen, påhviler det entreprenøren at lukke eventuelle borehuller. Anvendelse af propper, som forsegles er ikke tilladt.

Resultater af asfaltanalyser og komprimeringskontrol skal fremsendes ufortøvet til tilsynet, og som dette er aftalt på opstartsmødet.

Ved borekerner, der udtages i forbindelse med kontrol, skal lagtykkelsen anføres, og der skal desuden anføres om klæbningen af den udlagte belægning er intakt. Borekerner skal på forlangende forevises tilsynet.

4.3 Kontrol ved entreprisestørrelse II

Der foretages opstartskontrol når udlægningen af et nyt asfaltlag påbegyndes uanset at den planlagte udlægningsperiode er mindre end 5 sammenhængende udlægningsdage.

Et kontrolafsnit defineres som en dagsproduktion, hvor en type asfaltmateriale er udlagt. Borekernernes tolerancer beregnes pr. dagsproduktion, dog på serier af mindst 6 borekerner. Hvis udlægningsmængden ved en dagsproduktion giver anledning til, at der udtages mindre end 6 borekerner, kan det undtagelsesvis være nødvendigt at samle to eller tre dagsproduktioner for at opnå mindst 6 borekerner.

4.3.2 Antal prøver ved igangsættelse af udlægning

Kontrol af Marshallprøvning jf. AAB udgår.
Det fastholdes, at entreprenøren skal udføre kontrol, med nedenstående egenskaber jf. AAB:

- <… … bitumenprocent … …>
- <… … kornkurve … …>
- <… … asfaltmaterialets maksimale densitet … …>
- <… … stenmaterialets densitet … …>
- <… … blødhedspuntk k&r på udgangsbitumen … …>

Entreprenøren skal udføre kontrol, med nedenstående egenskaber jf. AAB:
- Indbygget hulrumsprocent [V_L], tolerance
- Komprimeringsgrad [K], tolerance
- Refleksion

4.3.3 Antal prøver ved fortløbende udlægning
Kontrol af Marshallprøvning jf. AAB udgår.
Det fastholdes, at entreprenøren skal udføre kontrol, med nedenstående egenskaber jf. AAB:
- <… … bitumenprocent … …>
- <… … kornkurve … …>
- <… … asfaltmaterialets maksimale densitet … …>
- <… … stenmaterialets densitet … …>

Entreprenøren skal udføre kontrol, med nedenstående egenskaber jf. AAB:
- Indbygget hulrumsprocent [V_L], tolerance
- Komprimeringsgrad [K], tolerance

4.3.4 Tolerancer
Krav vedrørende Marshallprøvning jf. AAB udgår.
Krav vedrørende bitumenprocent, kornkurve og stenmaterialets densitet jf. AAB fasthol-des.

5. Afhjælpning

Hele afsnittet i AAB udgår og erstattes af det i SB § 36 anførte.

Annex C Overview table of bituminous binders

			KLIVE18#01			KLIVE18#02			KLIVE18#03		
			Bitumen	Asphalt	Contractor's data	Bitumen	Asphalt	Contractor's data	Bitumen	Asphalt	Contractor's data
Testmethod	**Standard**	Unit	Original bitumen	Recovered binder	Specification	Original bitumen	Recovered binder	Specification	Original bitumen	Recovered binder	
Penetration at 25 °C	DS/EN 1426:2015	0,1 x mm	81	54	40-100	71	47	40 - 100	64	54	40 - 100
Softening Point Ring & Ball	DS/EN 1427:2015	°C	70,6	61,2	> 75	76,6	75,2	80,0	76,0	75,4	80
Elastic Recovery at 10 °C	DS/EN 13398:2017	%	86,8	75		77,8	78,3		79,8	76,3	
elongation or length at rupture		mm	200	200		200	200		200	200	
Force Ductility at 5 °C	DS/EN 13589:2018	J/cm^2	3,28	5,11		6,89			7,18		
elongation or length at rupture		mm	400	400		rupture at 335			rupture 295-390		
Rheology - DSR (-10 °C - 100 °C ; 0,01 Hz - 30 Hz)	DS/EN 14770:2012	MPa & °									
Rheology - MSCRT (50 °C,. 60 °C & 70 °C)	DS/EN 16659:2015	%									
Infrared spectroscopy		Absorbans									
Ash or remaining filler content	In-house, gravimetric, 430 °C	%		1,02		0,67	0,60		0,58	0,72	

Data/datafil available	(green)
Data/datafile not available	(red)
Data not expected	(grey)

			KLIVE18#05			KLIVE18#06			KLIVE18#07		
			Bitumen	Asphalt	Contractor's data	Bitumen	Asphalt	Contractor's data	Bitumen	Asphalt	Contractor's data
Testmethod	**Standard**	Unit	Original bitumen	Recovered binder		Original bitumen	Recovered binder		Original bitumen	Recovered binder	
Penetration at 25 °C	DS/EN 1426:2015	0,1 x mm	88	59	77	49	38		49	31	
Softening Point Ring & Ball	DS/EN 1427:2015	°C	69,6	64,6	75,0	52,4	54,2		52,4	58,4	
Elastic Recovery at 10 °C	DS/EN 13398:2017	%	86,1	78,3		5,0	0		7,3	0	
elongation or length at rupture		mm	200	200		50 - 56	0		0 - 60	0	
Force Ductility at 5 °C	DS/EN 13589:2018	J/cm^2							0	0	
elongation or length at rupture		mm							0	0	
Rheology - DSR (-10 °C - 100 °C ; 0,01 Hz - 30 Hz)	DS/EN 14770:2012	MPa & °									
Rheology - MSCRT (50 °C,. 60 °C & 70 °C)	DS/EN 16659:2015	%									
Infrared spectroscopy		Absorbans									
Ash or remaining filler content	In-house, gravimetric, 430 °C	%	0,67	0,63		0,74	0,85		0,58	0,68	

Annex D Overview table of asphalt materials

Test or characteristica	Standard	Unit	KLIVE18#01 Analysis	KLIVE18#01 Contractor data / specification	KLIVE18#02 Analysis	KLIVE18#02 Contractor data / specification	KLIVE18#03 Analysis	KLIVE18#03 Contractor data / specification	KLIVE18#05 Analysis	KLIVE18#05 Contractor data / specification	KLIVE18#06 Analysis	KLIVE18#06 Contractor data / specification	KLIVE18#07 Analysis	KLIVE18#07 Contractor data / specification
Binder content	DS/EN 12697-1:2006 or DS/EN 12697-39:2012	%	6,4	6,9	6,7	6,9	6,3	6,5	7,1	7,1	7,2	7,1	6,1	6,9
Aggregate density	DS/EN 1097-6:2013	Mg/m³	2,715	2,73	2,726	2,720	2,916	2,940	2,723	2,730	2,720	2,730	2,702	2,760
Marshall density	DS/EN 12697-6:2012	Mg/m³	2,400	2,383	2,387	2,390	2,536	2,550	2,348	2,380	2,376	2,360	2,320	2,410
Marshall compaction temperature	DS/EN 12697-30:2012	°C		155		150		149 - 155		155				
Maximum density	DS/EN 12697-5:2010	Mg/m³	2,454	2,447	2,451		2,610		2,434		2,429		2,455	
Void content	DS/EN 12697-8:2003	%	2,3	2,0	2,7	2,6	2,8	2,7	3,6	2,4	2,2	3,3	5,5	2,4
Void in Mineral Aggregate		%	17,2	18,1	18,3	19	18,6	18,9	19,9	19,0	18,9	19,7	19,4	18,7
Void filled with binder		%	87	89,1	85	86	85	86	82	87	88	83	72	87
VB/VS ratio			0,18	0,20	0,191	0,202	0,193	0,200	0,204	0,204	0,205	0,205	0,172	0,201
Gradation	DS/EN 12697-2:2015													
11,2 mm sieve		%	100	100	100	100	100	100	100	100	100	100	100	100
8 mm sieve		%	97	95	95	95	97	95	95	94	94	96	94	95
5,6 mm sieve		%	67	61	66	64	62	61	62	62	63	63	55	54
4 mm sieve		%	50	46	40	44	41	40	42	45	45	44	38	37
2 mm sieve		%	30	31	30	32	29	28	28	32	31	29	26	27
1 mm sieve		%	23	23	24	25	23	23	20	23	23	21	21	21
0,5 mm sieve		%	19	17	20	21	21	19	16	17	18	16	18	17
0,25 mm sieve		%	16	14	17	16	17	15	13	13	14	13	16	14
0,125 mm sieve		%	13	11	15	13	14	12	11	10	12	10	13	10
0,063 mm sieve		%	10,2	10,0	12,4	9,2	11,6	9,4	9,7	10,00	9,8	8,5	10,5	8,5
Gyratory Compaction	DS/EN 12697-31:2007													
Density after 200 gyrations		Mg/m³	2,415		2,423		2,588		2,379		2,392		2,424	
Void after 200 gyrations		%	1,56		1,58		0,83		2,28		1,53		1,27	
Compaction Energy Index			5,8		7,7		0,1		19,5		2,6		43,9	
ISTM modulus														
10 °C - mean (std) Marshall compacted sam	DS/EN 12697-26:2012 Annex C	MPa		4.900		5.020		5.827						
Density of samples	DS/EN 12697-6:2012	Mg/m³	2,420		2.438		2,587		2,413		2,43		2,427	
10 °C - mean (std) [gyratory sample @ 200]	DS/EN 12697-26:2012 Annex C	MPa	5.376 (334)		8.213 (806)		9.655 (641)		4.383 (281)		9.638 (637)		12.249 (1.269)	
20 °C - mean (std) [gyratory sample @ 200]	DS/EN 12697-26:2012 Annex C	MPa	2.469 (238)		2.569 (137)		3.507 (207)		1.835 (120)		4.055 (507)		5.903 (809)	
10 °C - mean (std) [plate compacted, cored]	DS/EN 12697-26:2012 Annex F	MPa												
20 °C - mean (std) [plate compacted, cored]	DS/EN 12697-26:2012 Annex F	MPa												
Wheel Tracking Test at 60 °C	DS/EN 12697-22 + A1:2007													
Wheel Tracking slope, WTS		mm/1000 cycles	0,03	0,031		0,05		0,024						
Rut Depth, RD		mm	2,6	1,9				1,48						
Proportional Rut Depth, PRD		%	6,4	3		5		3,6						

NCC	
PEAB	
VTI	
TI	

Annex E Metodebeskrivelse for termografisk måling - UDKAST

Introduktion

Denne metode beskriver, hvordan temperaturen måles på overfladen af vejfladen direkte bag asfaltudlæggerens afretter ved hjælp af termografi. Termografi indebærer kvantificering af infrarød overfladestråling. Den infrarøde stråling tilhører det elektromagnetiske spektrum med bølgelængder inden
for 0,76 – 100 μm. Ved at sammenligne energi pr. bølgelængde kan temperaturen bestemmes. Metoden kan anvendes til alle varmblandede belægninger.

Metoden er beregnet til at bestemme temperaturvariationen ved udlægningen af belægningsmasser. Når koldere overflader end beregnet registreres kan der laves en opgørelse af risikoen for kvalitetsbrister for belægningsoverfladen.

Asfaltudlægger skal monteres med udstyr til infrarød temperaturmåling af asfaltmassen umiddelbart direkte bag afretteren. Målinger skal forekomme i realtid og kontinuert under udlægningen, for alle varmblandede asfaltsektioner der falder ind under den givne entreprise. Heraf skal entreprenøren levere data der inkluderer temperaturmateriale med tilhørende GPS-koordinater, mv.

Formålet er at evaluere fordelene ved at monitorere og dokumentere temperaturfeltet af asfalten der lægges ud. Herved skal kvalitetssikringen af asfaltarbejder med varmblandet asfalt tilføjes et led, der har potentiale til at medfør en forøget kvalitet af de belægninger der lægges ud.

For entreprenøren kan monitoreringen i realtid på sigt give entreprenøren mulighed for at optimere på de metoder de har der påvirker asfaltens temperatur ved udlægningen. Dette kan være under selve udlægningen, eller ved en daglig gennemgang og analyse af de termiske data der indsamles ved asfaltarbejder. Resultatet heraf vil være asfaltlag der er bedre komprimeret end ellers.

Begrebsforklaring

Belægningspassets bredde	Ordet refererer til bredden på asfaltoverfladen som udlæggeren efterlader bag sig ved en enkelt udlægning. I daglig tale anvendes ordet også bare for overfladen efterladt bag udlæggeren dog uden at længden er klart defineret. Passets kanter er de samme som belægningsoverfladen kanter efter passet.
Indfaldsvinkel	Vinklen mellem belægningsoverfladens normal og kameraets centerlinje ved måling.
Målebredde	Banebredde fra den ene kant til den anden af belægningen bag udlæggeren.
Enkeltværdi	Den måleværdi, $x_{(i)}$, som registreres indenfor maksimalt 2 sekunder. Måleværdien er en middelværdi af temperaturen fra flere måloverflader.
Måloverflade	Den overflade som momentant aflæses og giver en målværdi.
Referencepunkt	Centerpunktet af en måloverflade
Termisk segregation	Termisk segregation er temperaturforskelle i varmblandet asfalt ved udlægning, der kan forårsage præmature skader, grundet øget modstand mod komprimering og arealer med forøget hulrumsprocent.
Kritisk temperaturdifferentiale (KTD)	Temperaturforskel i asfaltmikset der kan forårsage termisk segregation. Temperaturdifferentialet må ikke spænde over mere end ±14 °C ift. den omkringliggende asfaltmasse.
Risikomåling	Belægningsoverflade som inkluderer enkelte målte niveauer der er lavere end de definerede værdier for maksimale temperaturdifferentialer eller ophørstemperatur. Dette set ift. gennemsnittet af omkringliggende målinger der ligger indenfor 10 cm². Overflader der udføres koldere end den optimale temperatur er også risikomålinger.
Risikoareal	Den summerede overflade af sammenhængende risikomålinger, for den analyserede belægningssektion. Er det summerede risikoareal mere end 10 cm² overgår det til beregning af risikoandel.
Risikoandel	Det summerede risikoareal, af arealer der overskrider 10 cm², for evalueringsområdet i relation til den totale belægningsoverflade, udtrykt i %.

Udstyr
Kameraspecifikationer

Krav til nøjagtighed og opløsning:

Sensoropløsning	x pixels horisontalt (X-akse) x pixels vertikalt (Y-akse)
Nøjagtighed af målinger:	+/- 2,0 °C
Minimumsvinkel for målevinkel:	90° horisontalt
Temperaturspektrum:	0 til 280 °C
Temperatur opløsning:	0,1 °C
Reproducerbarhed af temperaturmålinger:	+/- 1,0 °C
Indfaldsvinkel:	45° til 90°

Termokameraet skal monteres på udlæggeren. Det skal aflæse og gemme belægningstemperaturer successivt mens udlæggeren bevæger sig fremad.

Kameraudstyret skal monteres bag på udlæggeren på en sådan måde at det er muligt at aflæse de termiske profileringsmålinger indenfor 3 m? bag afretteren på udlæggeren og i den fulde bredde af udlægningen fra den pågældende maskine.

Det samme punkt på X-aksen, måles til en ny værdi på Y-aksen indenfor 2 sekunder.
Dette skal der redegøres for i dataleverancen om hvorvidt er overholdt.

Andet udstyr

Datalagringsmedie
Data skal enten gemmes på termokameraet eller i et andet datalagringsmedie således at det er muligt at præsentere data efterfølgende. En datalagringsenhed skal være robust, forstået på den måde at den skal være af en udformning og monteres på en måde hvorved det dataene er sikret!

GPS-udstyr
Positioneringen skal forekomme ved en GNSS RTK måling

Beslag til montering af udstyr
Der skal installeres fornødne beslag til at det af udstyret der skal fastmonteres kan installeres korrekt. Dette vil i alle tilfælde betyde at IR kameraet skal fastmonteres, men hvad der derudover skal fastmonteres afhænger af udstyrets sammensætning og må af entreprenøren og leverandøren vurderes for hver udstyrspakke.

Kalibrering, kontrol
Kalibrering leveres normalt af forhandleren af udstyret. En grov kontrol udføres ved en jævnførelse med et indstiks-termometer med en præcision på ± 1 °C. Indstikkets dybde skal være mellem 10-20

mm. Kontrollen skal foretages med det samme efter termokameraet har registreret dets måleværdi. Det er en grov kontrol fordi temperaturen kan falde med op til ca. 20 °C per minut efter asfaltmassen forlader strygejernet.

Det mindste antal af disse målinger er et punkt fra første læs og et fra det sidste på den strækning der bliver udlagt, dog mindst to gange dagligt. Koordinaterne for disse målinger skal registreres.

Registrering af data

Positionering
Måledata skal registreres samtidigt med de aktuelle længdemålinger, således at der kan laves grafiske print efterfølgende.
Planreferencesystem skal være ETRS89/UTM32.
Højdereferencesystem skal være DVR90.
Positioneringen skal forekomme ved en GNSS RTK måling og med en nøjagtighed på 5 cm i planet og 5 cm i højde.
GNSS positionen skal kontrolleres mindst to gange dagligt.

Antal målinger pr sekund
Det samme punkt på X-aksen, måles til en ny værdi på Y-aksen indenfor 2 sekunder.
Dette skal der redegøres for i dataleverancen om hvorvidt er overholdt.

Ansvarlige for dataindsamling samt dataejer

Typer af data

Skal der senere være krav om at data skal sendes ved en cloudløsning?

For enhver given række temperaturmålinger tilknyttet et koordinat værdi på Y-aksen (længdemålingerne), skal der være data for hhv.:

Dato	[DD:MM:ÅÅÅÅ]
Tid	[TT:MM:SS]
Længdegrad	(decimalgrader, med min. 6 betydende cifre)
Breddegrad	(decimalgrader, med min. 6 betydende cifre)
Højde	
Distance	[m]
Kørselsretning for udlægger	(vinkelgrad, med uret fra nord)
Hastighed for udlægger	[m/s]
Luftfugtighed	[%]
Lufttryk	[hPa]
Lufttemperatur	[°C]
Vindhastighed	[°C]
Bredde på venstre udvidelse af strygejernet	[mm]
Bredde på højre udvidelse af strygejernet	[mm]

Andre data påkrævet
Udlæggers stop undervejs og varighed af stop

Andre mulige data (ikke påkrævede)
Temperatur i sneglen

Analyse

Frasortering af fremmedobjekter
Ved evaluering skal datagrundlaget justeres for fremmede objekter. Fremmede objekter er typisk personale der passerer måleområdet hvorved den infrarøde stråling reduceres. Data fra fremmede objekter som er mindre end 90 °C skal fjernes manuelt eller automatisk. Det skal dog tydeliggøres at disse data ikke er relevante. Måleværdier under 90 °C ved varmblandet asfalt fjernes, det vil indirekte sige andre objekter som maskinelt udstyr og personale som er kommet inden for måleområdet.

Evalueringsområdet begrænses til 30 cm fra belægningspassets kanter.

Rapportering af resultater

Afleveringer

Resultaterne af målingerne skal præsenteres i form af et profil med individuelle værdier, hvor y-aksen refererer de aktuelle længdemålinger. Hver linje af data på x-aksen skal have datapunkter tilknyttet beskrevet i punktet 'Typer af data' under sektionen Registrering af data.
Formater af disse afleveringer skal være som txt- csv- og/eller xlsx-fil.
Yderligere skal disse filer indeholde en data-header med følgende informationer:

<table>
<tr><th colspan="6">Information i data-header for resultattabel</th></tr>
<tr><th>#</th><th>Beskrivelse</th><th colspan="4">Eksempel</th></tr>
<tr><td></td><td>Entreprenør</td><td colspan="4"></td></tr>
<tr><td></td><td>Entreprenørens kontaktperson</td><td colspan="4"></td></tr>
<tr><td></td><td>Måle-operatør</td><td colspan="4"></td></tr>
<tr><td></td><td>Målefirmaets kontaktperson</td><td colspan="4"></td></tr>
<tr><td></td><td>Periode</td><td colspan="4"></td></tr>
<tr><td></td><td>Tid</td><td colspan="4"></td></tr>
<tr><td></td><td>Vejrdata</td><td colspan="4"></td></tr>
<tr><td></td><td>Belægningstype</td><td colspan="4"></td></tr>
<tr><td></td><td>Lag</td><td colspan="4"></td></tr>
<tr><td></td><td>Belægningstykkelse - planlagt</td><td colspan="4"></td></tr>
<tr><td></td><td>Belægningstykkelse – Gennemsnitlige realiserede</td><td colspan="4"></td></tr>
<tr><td></td><td>Lokation</td><td colspan="4"></td></tr>
<tr><td></td><td>Vejnummer</td><td colspan="4"></td></tr>
<tr><td></td><td>Kilometrering(er)</td><td>Fra km</td><td></td><td>Til km</td><td></td></tr>
<tr><td></td><td>Total længde af sektionen</td><td colspan="4"></td></tr>
<tr><td></td><td>Planlagt lagtykkelse</td><td colspan="4"></td></tr>
<tr><td></td><td>Fabrikant – IR system</td><td colspan="4"></td></tr>
<tr><td></td><td>Model – IR system</td><td colspan="4"></td></tr>
<tr><td></td><td>Fabrikant – Udlægger</td><td colspan="4"></td></tr>
<tr><td></td><td>Model – Udlægger</td><td colspan="4"></td></tr>
<tr><td></td><td>Laterale mellemrum mellem temperaturmålinger [mm]</td><td colspan="4"></td></tr>
<tr><td></td><td>Længdegående mellemrum mellem temperaturmålinger [mm]</td><td colspan="4"></td></tr>
<tr><td></td><td>Afstanden mellem infrarøde scanner og asfalten</td><td colspan="4"></td></tr>
<tr><td></td><td>Målefrekvens</td><td colspan="4"></td></tr>
</table>

	Længde, strygejern basis	
	Længde, strygejern venstre del	
	Længde, strygejern højre del	
	Kommentarer	