Low rolling resistance pavements in Denmark

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ABSTRACT

Low rolling resistance pavements can reduce fuel consumption by 4%.In Denmark the CO2 emission from the road transport alone is estimated to 4,6 mill ton pr. year. Implementing low rolling resistance pavement on the entire 4000 km of state roads in Denmark will provide a reduction in CO2 emission by 160.000 tons pr. year and saving the road users by 64 million litre of fuel.
Approximately one fourth of the total energy consumption in Denmark is consumed by the road transport, a consumption that is continuously growing. About one third of the energy consumption from the road transport comes from overcoming rolling resistance between the tire and road. In 2011 Danish national funding gave the possibility to initiate the COOEE project, CO2 emission reduction by exploitation of rolling resistance modelling of pavements. The project involved two universities, Roskilde University and the Technical University of Denmark, the Scandinavian contractor NCC roads and the Danish Road Directorate.
The challenge was to develop a road pavements with low rolling resistance that still provide other functionalities as friction to support traffic safety and low noise emissions.
In Denmark three tests sections has been constructed between 2012 and 2014 – the paper presents the experience from construction these pavements as well as the obtained functionalities such as rolling resistance, skid resistance and evenness.

Keywords: Emissions, Friction, Macro Texture, Rolling resistance, Surface Texture

1. INTRODUCTION

In Denmark, one fourth of the total energy consumption has been recognized as associated to the road transportation sector and Rolling Resistance (RR), which develops between tire and pavement, can dissipate up to one third of that energy. Even if RR has been studied for decades, pavement mix design and construction of road pavements that provide a low rolling resistance without losing skid resistance have not been deeply investigated yet. In 2012, based on this scenario, a Danish national funding financed the COOEE project (CO2 emission reduction by exploitation of rolling resistance modelling of pavements). The challenge was to establish a scientific background for developing pavements with low rolling resistance that still satisfy safety standards providing at least 15 years durability as achieved by the other pavement types used in Denmark [1]. Because Stone Mastic Asphalt (SMA) is one of the most common surface layers adopted on the Danish road, the COOEE aimed to optimize its gradation with the goal of reducing the rolling resistance.

From the pavement point of view, many different investigations have been completed focusing on the study of the influence of road properties on the rolling resistance losses. Texture and road smoothness have been commonly identified as the pavement properties which introduce sensible influence on the RR [2,3]. The smoother the road the lower was the rolling resistance. Sandberg in 1990 [4] investigated the effect of macro and megatexture on fuel consumption comparing different texture wavelengths and concluded that the smoothest road may have up to 11 percent lower fuel consumption than the roughest road when comparing textures on a 0.6 to 3.5 m wavelength. The rolling resistance characteristics of New Zealand road surfaces [5] showed that increasing 1 mm texture might lead into an increase in RR by 44% when the smoothness of the pavement was 1 m/km. A Dutch study [6] highlighted how positive effects of texture could be dominated by other pavement properties. In addition, comparisons between asphalt and concrete pavements did not provide statistically significant differences. Ullidtz et al. [7], comparing rolling resistance loss and dissipated energy under Heavy Falling Weight Deflectometer (HFWD) on four different pavement structures, found that pavement deflection might affect rolling resistance by at most 4 percent in case of trucks and much less for passenger cars.

In general, all the field tests confirmed the influence of pavement texture, smoothness and stiffness but it is not yet clear how these properties might interact and be affected by the other pavement variables and tire characteristics.

The present paper summarizes the results collected from the construction of the COOEE pavements and their corresponding rolling resistance characteristics. Different pavement structures have been resurfaced with low rolling resistance SMAs. Mix design, volumetric characteristics of the paved mixtures will be described together with Mean Profile Depth (MPD), Friction and RR.

2. COOEE PROJECT PROGRAM DESCRIPTION

The first COOEE test section was paved in Stensved in 2012. The pavement construction provided information about the COOEE mixtures which have been followed during the construction of the other two pavements in Langeskow and Sorøvej between 2013 and 2014 respectively.

On each test section, different SMAs were paved and the respective properties, such as MPD, Friction and RR, monitored every year. COOEE SMAs, with a maximum nominal size respectively of 8 mm (SMA8 COOEE) and 6 mm (SMA6 COOEE), were appropriately developed by NCC aiming an optimized texture capable of inducing a reduction in RR. The adopted reference was a conventional 0-8 mm SMA used in Denmark. The Technical University of Gdansk (TUG) Trailer, equipped with three different types of tire, has been used to monitor rolling resistance. The SRTT 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 Michelin Energy (MCEN) has been used in 2012 while in the following two years (2013 and 2014) the Michelin Primacy (MCPR) became the application of choice. Technical information about the adopted tires and measurement procedures have been summarized by Pettinari [8] and Sandberg et al. [9]. All the measurements were collected without any traffic interruption and, because of the TUG trailer configuration (Figure 1), the data were captured from the pavement section in between the wheel paths. MPD and Friction were measured on the wheel paths following the respective standard procedures [10, 11].

Figure 1: Representation of the measurements procedure

3. COOEE TEST SECTION IN STENSVED, 2012

3.1 Mixtures volumetric optimization and field workability evaluation

The COOEE SMAs gradation was investigated with the goal of producing dense and durable surface structure with low rolling resistance properties. Not only the aggregates skeleton but also the mortar components, as function of different filler sources, have been investigated and appropriately optimized to reduce relative movement between the stone aggregates of the surface. In fact, the mortar is the sum of different filler fractions, binder, and stabilizing additive and it represents a fundamental component of the SMA. Because of the relative large amount of filler, the type and quality plays a significant role in the properties of SMA mastics and mixtures. Mineral fillers affect workability, moisture resistance, stiffness, and aging characteristics of hot mix asphalt [12, 13, and 14]. Therefore, the effects of different mineral fillers on SMA mastics and mixtures need to be examined.

The mortar component of SMA6 and SMA8 COOEE was studied using Tumbler Abrasion test (EN 12274-7) [8]. It should be mentioned that mortar optimization has been investigated comparing mortar samples containing the same amount in weight of total filler. Two different limestone fillers, Portland cement and aggregates filler have been combined in different proportions and the adopted solution had the following percentages:

- Portland cement 20%.
- Limestone filler 45%.
- Aggregates filler (granite) 35%.

The gradation of the SMA8 COOEE has also been optimized comparing different percentage of passing the 4 mm sieve. The application of choice was represented by the solution b with a passing percentage to the 4 mm of approximately 45% which provided a most homogenous texture and proper workability (Table 1).

Table 1: Average Volumetric properties and MPD for the COOEE mixtures

	SMA6 COOEE	SMA8 COOEE-a	SMA 8 COOEE-b
Av. Air Voids (%)	9.9	8.2	7.7
S.D. Air Voids (%)	1.5	1.1	2.6
% of Mars. Density (%)	94.2	94.5	95.0
S.D. % Mars. Density (%)	1.6	1.1	2.7
MPD (mm)	0.70	0.72	0.71
S.D. MPD (mm)	0.05	0.05	0.05

3.2 Low Rolling Resistance test section in Stensved

The first COOEE test section, where rolling resistance has been measured, is in Stensved. The main road 619 was paved from km 9.8 to 11.0 on the left line with the SMA6 and SMA8 COOEE while on the right line a conventional SMA8 Reference was used. Two different compaction methods have been adopted on the SMA8 COOEE. The last 350 meters (from km 10.65 to 11.00) have been rolled applying vibrations while a static configuration of the roller has been used during the compaction of the first 250 meters and of the SMA6 COOEE. Only 1 km of the test section will be investigated and the first and the last 100 meters won't be included in the evaluation of the MPD, Friction and RR.

The binder content was optimized to produce compacted mixtures with approximately 4% air voids. Based on the adopted mix designs, target voids and trial productions on the asphalt mixing-plant, the bitumen content obtained for both SMA8 and 6 COOEE was 7.5% and 7.6% respectively. The reference mixture has 6.9%. In the figure below the percentage of passing to some significant sieves are represented:

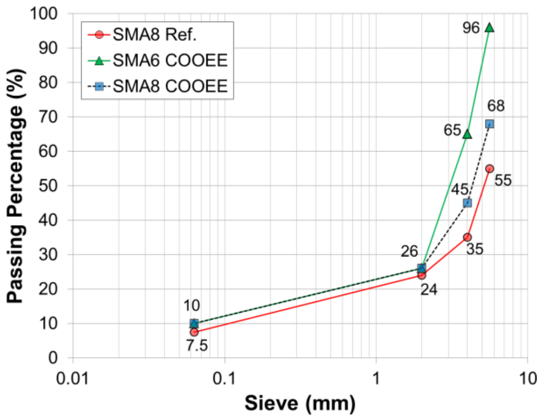

Figure 2: Mixture gradation from Stensved, 2012

Volumetric properties have been controlled on the different specimens cored from the test section. In relation to the layer thickness and paving operations, the degree of compaction achieved satisfied the design requirements. For all the studied mixtures, approximately 98% of Marshall Density was reached in the field.

Table 2: Average Volumetric properties for the COOEE mixtures on Stensved

Stensved 2012	**SMA 6 COOEE**	**SMA 8 COOEE**	**SMA 8 Reference**
Asphalt Density (g/cm^3)	2.285	2.371	2.350
Marshall Av. Air Voids (%)	6.0	2.2	3.6
% of Mars. Density (%)	98.1	97.7	98.4
Av. Air Voids (%)	4.4	8.1	5.1
Av. Layer Thickness (cm)	2.0	2.4	3.0
S.D. Layer Thickness (cm)	0.3	0.4	0.2

The drilled samples were also used to verify the quality of the adopted aggregates. Different thin sections were produced and analyzed with the microscope in order to detect critical weaknesses of the aggregates. The analysis of the thin section photos showed that the compaction procedure had generated many cracks in the aggregates which might be critical for the durability of the COOEE pavements.

The surface properties such as MPD and Friction, following the ISO 13473-1 and the CEN/TS 15901-5 respectively, were measured since the test section has been paved (Figure 3). Friction measurements confirm that safety requirements were satisfied in all the studied cases.

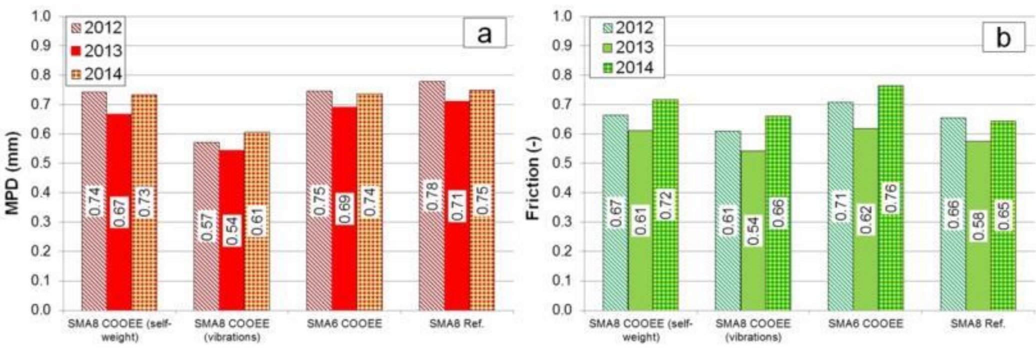

Figure 3: MPD and Friction from 2012 to 2014

In general average COOEE mixtures have lower MPDs than the reference while Average Friction coefficient of the developed asphalt mixtures was generally higher. Only SMA8 COOEE rolled applying vibrations exhibited Friction characteristics below the ones measured on the reference but still sensibly above the Danish requirements which for the studied road is 0.40. This satisfies one of the main objectives of the Cooee project which was to produce, using same maximal nominal size of the aggregates, asphalt mixtures with reduced texture depth but still capable of providing and guaranteeing high safety standards.

Rolling Resistance measurements were also performed every year. A temperature correction factor has been used to obtain RR coefficient at the reference temperature of 25°C [15]. In this case, the average RR coefficients have been compared to ones measured on the Reference along the same road coordinates. The collected results highlighted that (Figure 4):

- Tire represents one of the most significant variables to consider for RR prediction and modeling.
- The COOEE mixtures showed reduced RR properties. The amount of reduction depends on the adopted tire.
- Further investigations are required to define, for each type of asphalt, the trend of variation of RR properties with time.

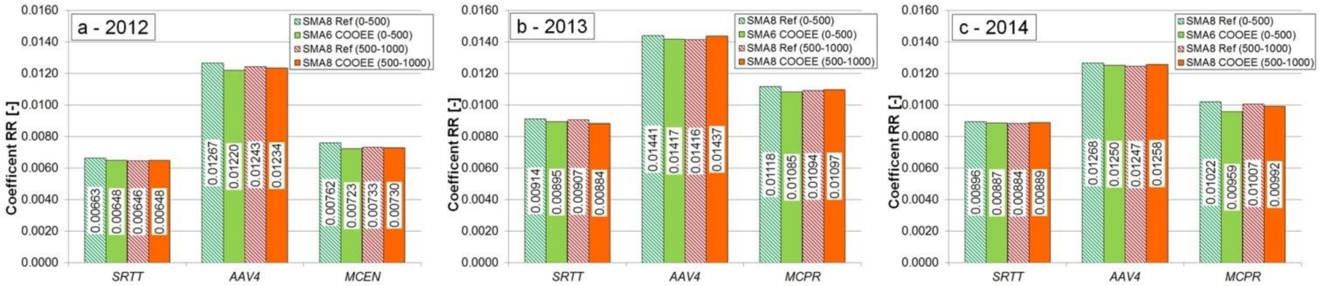

Figure 4: Average RR coefficient on Stensved from 2012 to 2014.

A better understanding of the results was provided by considering the following ratio:

$$RR\ Ratio\ (\%) = RR_{COOEE}/RR_{Ref.} \times 100$$

where RR_{COOEE}, $RR_{Ref.}$ are the RR coefficients measured on the same longitudinal coordinate. Based on the collected results, the following comments can be assessed (Figure 5):

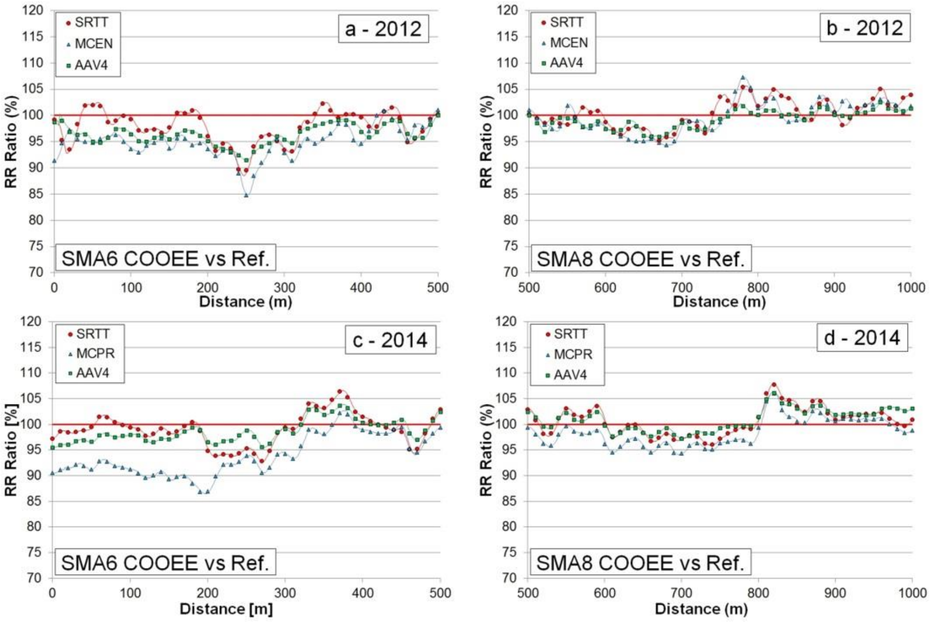

Figure 5: RR Ratio from 2012 and 2014.

- The SMA6 COOEE reached a peak of reduction in RR of 15% and an average of circa 5% on the first 250 meters. The longitudinal profile characteristics on the SMA6 from 250m to 500m might have hidden the effect of the texture on the RR properties (Figure 5a, 5c). The peak of reduction in RR introduced by the SMA8 COOEE was equal to 6% on an average of 3%. Also in this case on the second half of the SMA8 COOEE, the contribution of the texture on RR was not captured even if the difference in MPD between COOEE and Reference was much higher because the SMA8 COOEE was compacted applying vibrations (Figure 5b, 5d).

- With regard to the SMA6 COOEE, apart from the data measured with Michelin tires which were not the same model during the different years, the average RR Ratio in 2012 was 96.5% for the first half and 97.5% on the second. In 2014 the difference on the first half of the section reduced and the Ratio raised to 97.7% while from 250 m to 500 m no significant differences were measured. On the SMA8 COOEE in 2012, the average RR Ratios were 98.1% and 101.4% respectively on the first and second half of the pavement section. In 2014 both Ratios increased, the first was 99.3% while the second 102.1%.
- It is important to highlight that small variations cannot be always considered significant because RR measurements are affected by the longitudinal profile properties. So, even if comparisons have been made on data collected from the sections having same longitudinal coordinates, it may be possible that longitudinal profile height was not perfectly the same on both lanes were RR measurements have been performed.
- Further investigation is required to define and understand evolution of the RR properties. RR trends described by the different tires during consecutive years were not consistent. Temperature correction factor must be deeply studied.

4. COOEE TEST SECTION ON LANGESKOV, 2013

4.1 Low Rolling Resistance test section in Langeskov

In 2013 the new COOEE test section was paved in Langeskow using oscillation method. A preliminary investigation showed no relevant differences on volumetric characteristics when the COOEE mixtures were compacted applying oscillation or vibration. Feedbacks from Stensved highlighted the need of using stronger aggregates and increasing the mixing time during mixture production. The source of the mineral aggregates was changed by the contractor to limit cracks in the aggregates. Because of the road geometry, both lanes were paved with the same mixtures consequently the effect of the longitudinal profile was not investigated. No reference mixture was paved in 2013.
The binder content was optimized in relation to the new mixture properties and equal to 8.1% and 7.6% respectively for the SMA6 COOEE and SMA8 COOEE. In the figure (Figure 6) below, the percentage of passing to some representative sieves are represented.

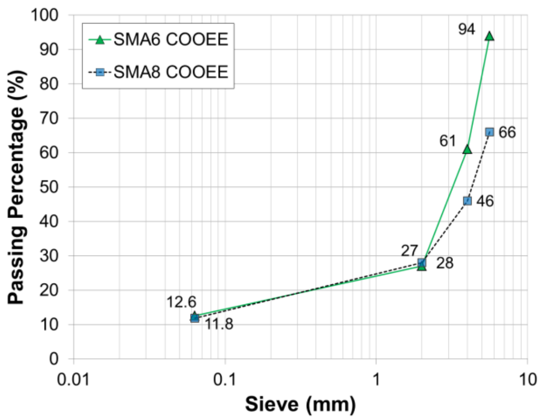

Figure 6: mixture gradation from Langeskov, 2013

Voids content and degree of compaction have been measured on the different specimens drilled from the test pavement. The table below (Table 3) summarizes the achieved volumetric characteristics.

Table 3: Average Volumetric properties of the COOEE mixtures on Langeskov

Langeskov 2013	**SMA 6 COOEE**	**SMA 8 COOEE**
Asphalt Density (g/cm^3)	2.384	2.409
Marshall Av. Air Voids (%)	2.1	1.9
% of Mars. Density (%)	96.9	98.0
Av. Air Voids (%)	5.1	3.8

Texture characteristics such as MPD and friction have measured in 2013 and 2014. The collected data are represented in Figure 7:

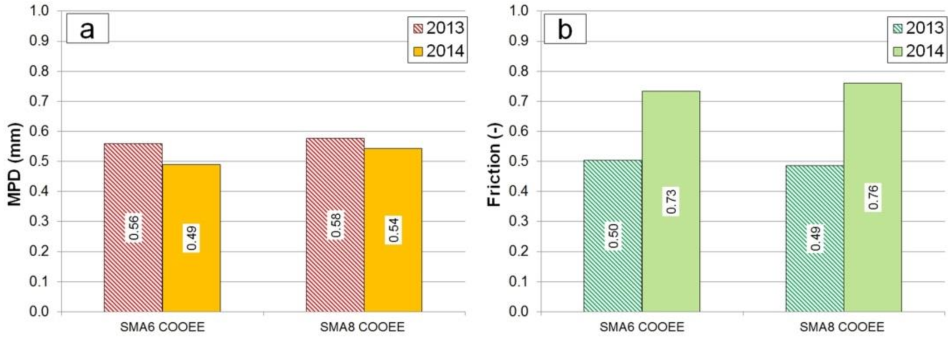

Figure 7: MPD and Friction from 2012 to 2014

As obtained in Stensved, the MPD of both SMAs was reduced from 2013 to 2014. The main peculiarity is the sensible increase in Friction which could have been provided by the new type of aggregates. All the Danish requirements have been fulfilled. With regard to the evolution of the Friction characteristics, data from 2015, which are not yet available, will provide a better understanding of the variation of surface characteristics.

RR measurements have been performed both years and all the collected RR coefficients have been converted, applying the temperature correction factor, to the corresponding coefficient at 25°C. Figure 8 summarizes the average RR coefficients measured on both SMA6 and SMA8 COOEE.

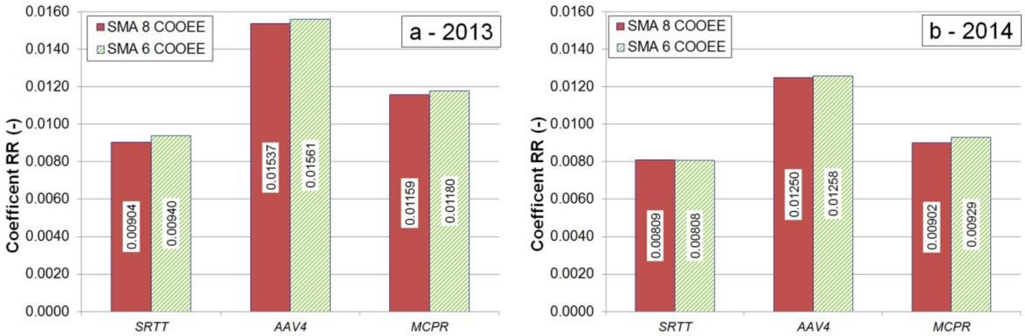

Figure 8: Average RR coefficient from 2013 and 2014

Based on the presented results, the following comments can be summarized:

- The RR of the SMA6 COOEE appears higher than the one measured on the SMA8 COOEE even if the difference in MPD, between the two studied cases, is not that significant. Both pavements have different longitudinal profile properties and this might also have an effect on the average RR coefficient;
- If compared to RR coefficients measured the same year on Stensved, the average values from Langeskov road are similar in 2014 but higher in the previous year. In both cases, textural properties between the pavements in Stensved and Langeskov are not comparable. In 2013, the bitumen on the surface was worn off by the traffic in Stensved while Langeskov had just been paved. In 2014, as confirmed by the MPD and Friction properties, the texture of the pavement in Langeskov was representative of an in-service pavement while in Stensved a sensible rise in MPD appeared.

5. COOEE TEST SECTION ON SORØVEJ AND DANISH STATE ROAD 2014

5.1 Mixtures volumetric optimization and field workability evaluation

The construction in Langeskov confirmed the validity of the COOEE mixtures from the rolling resistance point of view. Because of the low traffic level, Langeskov could not have been used to verify the texture stability of the new mixture consequently a new test section in Sorøvej has been paved. Some minor variations on the mixture recipe have been applied in order to improve workability. In the figure below the gradations adopted in Sorøvej are represented (Figure 9).

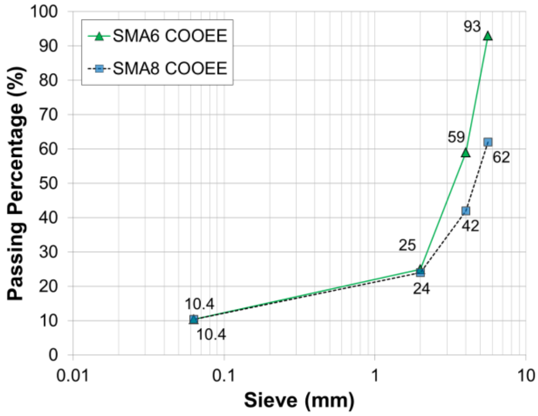

Figure 9: mixture gradation from Sorøvej, 2014

The amount of adopted bitumen, directly measured from samples collected at the paver machine, was 7.8% and 7.4% for the SMA6 and SMA8 COOEE respectively. The volumetric characteristics measured on the drilled specimens from the pavement and MPDs are summarized in Table 4. Friction has not been measured in 2014.

Table 4: Average Volumetric properties of the COOEE mixtures on Sorøvej

Sorøvej 2014	**SMA 6 COOEE**	**SMA 8 COOEE**
Asphalt Density (g/cm^3)	2.353	2.396
Marshall Av. Air Voids (%)	3.8	2.5
% of Mars. Density (%)	97.1	97.3
Av. Air Voids (%)	6.6	5.2
MPD (-)	0.584	0.639

The RR measurements were collected over the studied pavements by the TUG trailer as preformed on the other test section in the same year. In Figure 10, the average RR coefficients for all the studied pavements and the three adopted tires are represented.

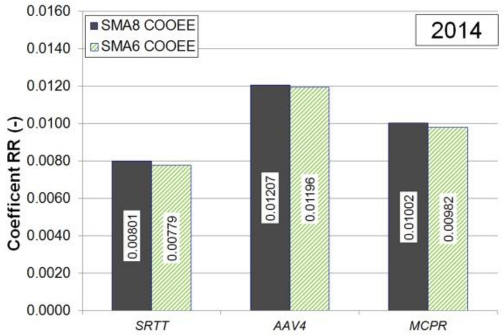

Figure 10: Average RR coefficient from 2014

Because the two COOEE mixtures have been paved on the same pavement structure but with different longitudinal profile characteristics, it should be highlighted that texture contribution on RR properties might result affected.

In general, with all the adopted tires, the SMA6 COOEE showed lower RR properties than the SMA8 COOEE. As assessed on the previous case, any comparison with measurements collected in 2014 on the other test sections should take into account the fact that the other pavements have been already exposed to traffic and consequently the surface properties cannot be considered comparable. The main objective of this test section is to verify the durability of the surface properties and consequently further measurements during the next years will be required to verify and validate the mixture stability.

The same year also some kilometres of the Danish road network have been monitored. The average MPD was equal to 0.945 mm and the collected RR coefficients were 0.0103, 0.0165 and 0.0140 for SRTT, AAV4 and MCPR respectively.

6. CONCLUSIONS AND RECOMMENDATIONS

The COOEE project centered the attention on the surface properties of the pavement aiming to design a more environmentally friendly road infrastructure by reducing rolling resistance and consequently vehicle CO_2 emissions. The main purpose of the project was to develop, without compromising safety requirements and durability, asphalt mixtures with optimized texture properties capable of generating reduced rolling resistance.

During the project, three SMAs have been paved on three different test sections. Functional properties and RR were monitored every year in order to study the evolution with time of these properties. Two asphalt mixtures were appropriately optimized, using a maximum gradation size respectively of 8 mm (SMA8 COOEE) and 6 mm (SMA6 COOEE), with the purpose of reducing the texture depth. The rolling resistance data have been collected in the field using the TUG trailer equipped with three different tires. The main and preliminary conclusions of this investigation are listed below:

- SMA gradation can be optimized to reduce rolling resistance properties of the pavement. In particular the results collected from the main road in Stensved showed that an average RR reduction of approximately 5% and 3% respectively with SMA6 & 8 COOEE has been achieved if compared to a reference SMA8. A peak of 15% with the SMA6 COOEE was also obtained even though further investigations are required to understand how texture and longitudinal profile might have interacted. The increase in MPD measured on the third year confirmed the issue related with the adopted aggregate source and the cracks in the aggregates detected from the thin section study;
- The new aggregates source used in Langeskov showed a reduced amount of cracks in the aggregates compared to the previous solution. From the rolling resistance point of view, the SMA6 COOEE seems to exhibit higher values than the SMA8 COOEE. The difference in MPD of the two mixtures was not significant and consequently the longitudinal profile configuration of the road might have affected the texture contribution;
- In Sorøvej because of the type and level of traffic, the test section represented an optimal solution for verifying the textural stability and mixtures durability. The available data, collected after the construction of the road in 2014, confirmed the reduced texture depth and the low rolling resistance properties. Compared to the average rolling resistance measured on the Danish road network, the COOEE mixtures paved in Sorøvej showed a reduction up to 20%. The evaluation of the field performances requires time and traffic consequently relevant results are expected during the next years.

Further investigations should be focused on the temperature correction factor and the influence of the longitudinal profile on the rolling resistance measurements. From the pavement point of view, stability and durability of the texture should be further investigated and in order to make these mixtures attractive the expected life should be comparable to the one achieved by conventional SMA.

7. ACKNOWLEDGMENTS

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