

Development and implementation of low rolling resistance pavement in Denmark

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En torno a una cuarta parte del consumo total de energía en Dinamarca proviene del transporte por carretera, una proporción que se incrementa de forma permanente. Un tercio de este consumo se debe a la resistencia a la rodadura entre el neumático y la carretera. Los pavimentos de baja resistencia a la rodadura pueden reducir el consumo de combustible en un 4%. En Dinamarca, las emisiones de CO₂ procedentes del transporte por carretera se estiman en $4,6 \times 10^6$ t/año. La implantación de un pavimento de baja resistencia a la rodadura en los 4.000 km de carreteras estatales del país permitirá reducir las emisiones en $1,6 \times 10^5$ t/año. La Dirección de Carreteras de Dinamarca ha estado trabajando desde 2010 en el desarrollo de un pavimento de carretera que reduzca la resistencia a la rodadura entre vehículos y pavimentos de carreteras. A tal fin, se han realizado cuatro bloques de pruebas, entre 2012 y 2016, en las carreteras en servicio de Dinamarca. En 2016 se realizaron pruebas adicionales aceleradas en VTI, en Suecia, donde se ensayaron varias mezclas de asfalto. Los resultados recogidos han demostrado que la baja resistencia a la rodadura SMA8 puede proporcionar estabilidad a la textura y resistencia al desgaste comparable a una SMA11 convencional.

Palabras clave: Dinamarca, consumo de energía, pavimentos de baja resistencia a la rodadura

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 tyre and road. Low rolling resistance pavements can reduce fuel consumption by 4%. In Denmark the CO₂ emission from the road transport alone is estimated to 4.6×10^6 t/year. Implementing low rolling resistance pavement on the entire 4000 km of state roads in Denmark will provide a reduction in CO₂ emission by 1.6×10^5 t/year. The Danish Road Directorate has since 2010 been working on developing a road pavement that reduces the rolling resistance between vehicles and road pavements. This has led to 4 tests sections established between 2012 and 2016 on in-service roads in Denmark. In 2016 an additional accelerated tests were performed at VTI in Sweden where several asphalt mixes were tested. The collected results have shown that the low rolling resistance SMA8 can provide texture stability and wearing resistance comparable to a conventional SMA11.

Keywords: Denmark, energy consumption, low rolling resistance pavement

1. Socio-economic incentive to implement pavements with low rolling resistance

Low rolling resistance pavements reduces CO₂ emissions from the road transport. This CO₂ emission can be translated to an economical benefit for the society. A key part of the research in low rolling resistance pavements has been to perform socioeconomic analyses. These analyses justify the eco-

nomic benefit to the society, when implementing low rolling resistance pavements on the state roads in Denmark.

Additional to lowering CO₂ emission, low rolling resistance pavements also reduces tyre/road noise. The socioeconomic benefit when lowering road traffic noise is significant. This means that the additional positive effects from lowering the tyre/road noise by low rolling resistance pavements provides extra beneficial value when calculating the socioecono-

Development and implementation of low rolling resistance pavement in Denmark

mic benefit. Especially the noise reducing effects plays a major role when using these pavements on high-trafficked roads in urban areas.

By adding the socioeconomic benefits from the reduced CO₂ emission and decreased noise emission, makes the use of low rolling resistance pavements very competitive as an initiative to reduce CO₂ emissions from the road transport, compared to other initiatives.

When calculating socioeconomic aspects of implementing low rolling pavements on the state roads, the outcome is highly dependent on the change in pavement condition, from the existing surface to the low rolling resistance surface, and the traffic amount on the given motorway.

To analyse the effect of implementing low rolling resistance pavements on the Danish state road, the socio economic benefit for a number of motorway sections has been calculated.

Included in the economic analysis are dense trafficked motorways around Copenhagen, the capital of Denmark, motorway M10 and M14, and a major motorway corridor across Denmark, Motorway M40. Also included in the analysis, are lesser trafficked motorways in the rural areas of Denmark, motorway M50 and M80. Table 1 shows that the motorways with the highest traffic density also have the highest unevenness, expressed by the International Roughness Index, IRI m/km. The pavement texture expressed as Mean Profile Depth (MPD) are similar for all analysed motorways.

When comparing the socioeconomic performance of the different motorways, it was decided to use the return factor for the investment when replacing the existing wearing course with a low rolling resistance pavement. The return factor expresses the factor of return for the public investment. Figure 1 shows the specific return factor if low rolling resistance pavements were implemented on the analysed motor-

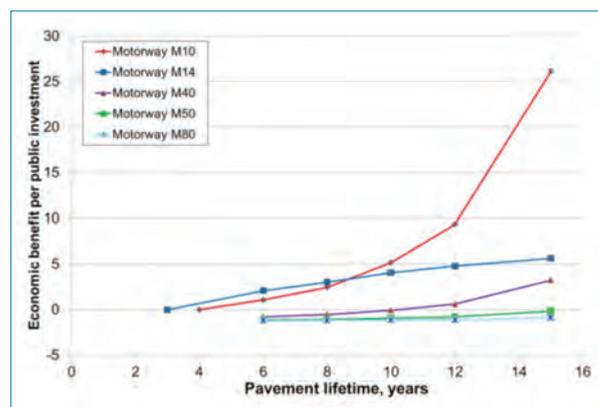


Figure 1. Economic effect by introducing pavements with low rolling resistance on motorways in Denmark, expressed as Economic benefit per public investment.

ways. When the return factor is positive, then the specific investment generates resource back into a society. The x-axis in figure 1 represent the year after construction. As an example, figure 1 shows, that for Motorway M10 the return factor is 0 four years after construction. This means that after year four the investment in a low rolling pavement on M10 has been paid back to the society and that the pavement starts generating an economic surplus for the society. After 14 years of lifetime the low rolling resistance pavement generates an economic surplus by a factor 25 to the society.

In general, Figure 1 shows that the highest benefit and where the low rolling resistance pavements have the highest return factor for the investment is around the bigger cities in Denmark, such as Copenhagen. This is due to the high traffic volumes and that Copenhagen area is the most populated area.

2. Development of low rolling resistance pavements

In Denmark, the study and development of low rolling resistance pavements started in 2012. Danish national funding

Table 1. Road sections in Denmark where the socio economic calculations has been performed.

	Motorway M10	Motorway M14	Motorway M40	Motorway M50	Motorway M80
Length of road [km]	55	68	174	183	104
Area [m ²]	710,000	640,000	1,480,000	1,550,000	840,000
IRI [m/km]	1.23	1.17	1	0.93	0.8
MPD [mm]	0.89	0.9	0.99	0.88	1.06
Traffic in AADT	84,000	49,000	50,500	37,500	14,300

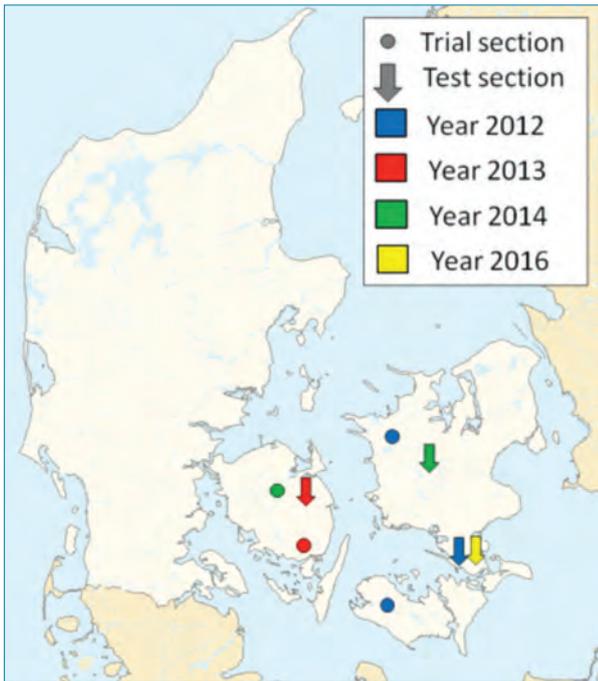


Figure 2 Illustration of the different low rolling resistance pavements in Denmark.

supported and 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 (RR) that still satisfy safety standards providing at least 15 years durability. Stone Mastic Asphalt (SMA) is most common pavement surface layer adopted on the Danish road network and the COOEE aimed at optimizing the mix design with the goal of reducing rolling resistance.

Four different test sections were paved since 2012 to 2016 supported, when necessary, by trial sections in order to evaluate all the relevant characteristics (Figure 2).

The first test section was paved in Stensved in 2012 where a reference and two different COOEE mixtures were paved over the same pavement structure on two parallel lanes. Based on this configuration, the real impact of texture depth on the RR characteristics was detected. In fact, RR properties are also affected by the longitudinal profile and the impact of texture depth on the RR characteristics of a pavement depends on the unevenness of the longitudinal profile. RR data were normalized with the corresponding RR measured on the reference mixture and the rolling resistance reduction due to the different textural properties was assessed. COOEE mixtures showed an initial reduction of rolling resistance proper-

ties of approximately 5 % if compared to a reference mixture [1]. The energy efficiency became more pronounced, with an improved RR reduction of 20 %, when the comparison was performed against an average RR measured on 100 km of conventional Danish state roads. The test section in Stensved is still monitored and measurements collected in 2015 had shown a lack in texture stability and durability.

In 2013 a new COOEE test section was paved in Langeskov using a different compaction procedure. The source of the mineral aggregates was changed by the contractor. The purpose of this change in the mix recipe was to reduce premature distresses due to broken stones caused by compaction. Langeskov confirmed the validity of the COOEE mixtures from the rolling resistance point of view but, because of the low traffic level, the test section could not be used to verify the texture stability of the new mixtures [2]. For this purpose, a new test section in Sorøvej was paved in 2014 and it is still monitored to document and evaluate texture changes.

The overall results of the COOEE project became a solid statement toward the implementation of low rolling resistance layers in the Danish road network. In fact, it has been shown that rolling resistance can be reduced by optimizing the asphalt mixture gradation. Performances of the low rolling resistance pavements should have been improved and the pavement construction has become a key factor for achieving the desired reduction in rolling resistance and durability. In fact, the low rolling resistance test section paved in Stensved during the COOEE project has been monitored for several years. A reduction in rolling resistance efficiency was measured together with an increase in texture depth. Some ravelling was detected and textural properties were consequently compromised (Figure 3).

Based on the presented outcomes, some changes in the mix design were approved and investigated. From the aggre-

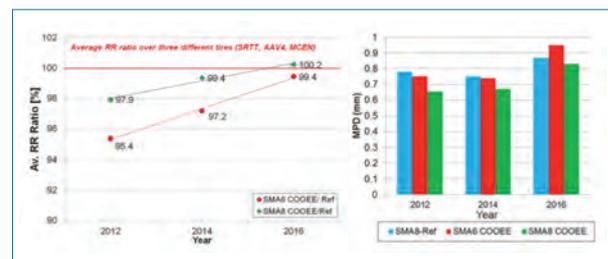


Figure 3 change in MPD and RR of the pavements from Stensved from 2012 to 2016.

Development and implementation of low rolling resistance pavement in Denmark

Table 2. Rolling resistance reduction measured on Kalvehave.

Tyre	SRTT		MCEN		AAV4	
	80 km/h	50 km/h	80 km/h	50 km/h	80 km/h	50 km/h
Meas. Speed	80 km/h	50 km/h	80 km/h	50 km/h	80 km/h	50 km/h
RR Ratio SMA6 C+ [%]	92.9	95.1	97.3	97.4	97.5	98.0
RR Ratio SMA8 C+ [%]	94.2	93.6	98.3	96.7	98.6	97.1
RR Ratio = $RR_{COOEE+} / RR_{ref} \times 100$						

gates point of view, it was recognized that granite offers high strength and high wear resistance and represent the optimal solution. With regard to the additives, 2 % of hydrated lime was included in the mixture to improve adhesion properties and reduce moisture sensitivity. Also the modification technique of the bitumen has a significant influence on the performance of the asphalt mixture under moisture conditioning [3]. In fact, polymers can sensibly change both adhesion and cohesion properties of the asphalt binder [4, 5]. This becomes more relevant by considering the fact that in the COOEE mixtures, the bitumen was mixed with polymers only during the asphalt mixture production. The use of pre-modified bitumen will improve adhesion and cohesion properties of the mixture and will guarantee a proper distribution of polymers in the mixture increasing the expected life time [6]. These mix adjustments, such as the use of hydrate lime and pre-modified bitumen, were adopted during the construction of the low rolling resistance test section paved in Kalvehave (2016). For practical reasons, these new mixtures have been named COOEE+. An extended RR measurement campaign was performed in 2016 with the TUG trailer. The pavements were measured at 3 different times of the day in order to get an evaluation of temperature effect. Furthermore, rolling resistance measurements were performed with three different tyre types and at two different speeds (50 km/h and 80 km/h). It must be recognized that, for each combination of tyre, speed, and day, several rolling resistance measurement runs have been performed.

RR reductions measured on the two different COOEE pavements in Kalvehave are summarized in Table 2. The pavement used as reference was a conventional SMA8.

With regard to the durability issue, it was expected that these changes in the mix design should improve texture stability and mixture performance. This has been studied using an intensive laboratory characterization and the Circular Road

Tester (CRT) which is an accelerated test device used to study wearing resistance of surface layers. A total of 14 different mixtures were tested with the CRT including the three paved in Kalvehave. In the next paragraphs, the most representative results collected from the Circular Road Tester (CRT) have been summarized and described.

3. Circular Road Tester description and configuration

The CRT is an accelerated loading facility capable to simulate pavement wearing and it has been used throughout the years for studies of wear from studded tyres on pavement surfaces as function of mix design and aggregate quality under various climatic conditions. To some extent also studies of permanent deformation at high surface temperatures have been performed.

The objective was to verify the durability of the different mixtures, evaluated as fretting and ravelling and texture changes, due to shearing action of the wheels on the pavement surface. During the simulation, test conditions such as temperature and moisture were controlled and changed to introduce seasonal effects. Due to electrical limitations, also the speed of the passing wheels has been changed. The applied load on each tyre was 450 kg. Both winter and summer tyres have been used in relation to the temperature conditions. A total of 350000 load passes have been applied and the overall simulation is summarized in the figure below (Figure 4). The main purpose of the test was to evaluate the behaviour of the low rolling resistance mixtures under different climate and loading conditions. The first 5000 cycles have performed using studded tyres aiming at removing the mortar from the surface of the different test slabs. From 5000 to 200000 cycles, the change in surface characteristics of the different mixtures have been analysed trying to reproduce summer conditions. During the last 30000 cycles the speed was increased up to 60

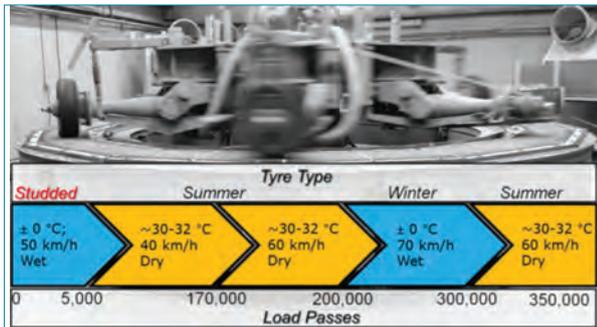


Figure 4: CRT test program.

km/h because the collected data were showing that all the studied materials had reached a steady state condition. From 200000 to 300000 cycles, effect of low temperatures and moisture were investigated. The last 50000 cycles were performed at high temperature and dry conditions.

All the tested mixtures were plant produced and laboratory compacted using a steel mould and light roller. Once the mould was preheated, a sample of hot mixed asphalt concrete was placed into the mould. Then a power rolling compactor was used to compact the slab and target the designed air voids content. A total of 28 slabs, two for each mixture, were produced and tested with the CRT.

Measurements consist of photographs, texture and transversal profile for wear and rut as shown in Figure 5. For each mixture and test interval, the average depth value of the transversal profile calculated over six different measurements will be described in the present article. As mentioned, the effect of texture has also been investigated. A 32 kHz texture laser was mounted on one of the arms of the CRT and used for measurement. A photo-sensor mounted between two slabs had been used to detect the end/start of a cycle and to distinguish between the different mixtures. Since these measurements were performed with a moving eccentricity, the lasers path should have been capable to traverse a large part of the slab with consecutive parallel lines providing a 3D scan of the different surfaces. These data are still under investigation and only average MPDs have been summarized.

4. Results analysis

4.1 Wearing and Rutting Depth evolution

Considering all the 14 mixtures, it must be recognized that wearing and rutting of the two slabs, representative of the same mixture, was consistent. The studded tyres used in the

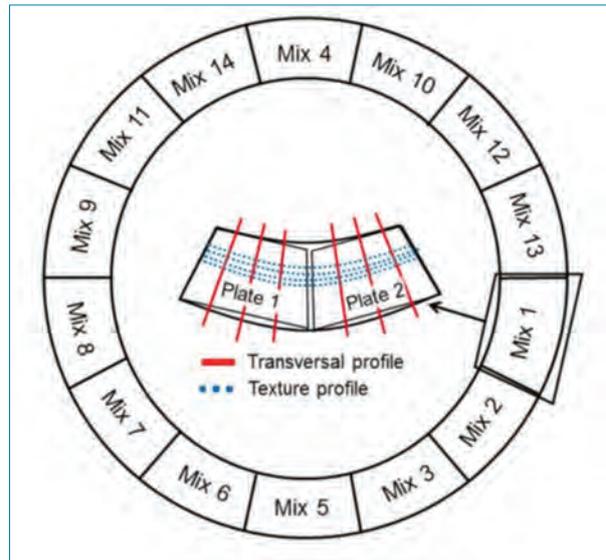


Figure 5: Drawing of the CRT configuration and measurements set-up.

first 5000 cycles worn the slabs by removing part of the mortar and bitumen covering the top aggregates. It should be noted that around 95 % of all changes in heights occurs during the first 100000 turns and consequently this part of the test is by far the most interesting to investigate in relation to wearing and rutting. This can also mean that, applying a constant load of 450 kg, the effect of change in temperature, water, tyre and speed during the simulation might not be significant in particular if chemical ageing cannot be accelerated. For a better understanding of the results only 5 out of 14 mixtures have been included in the Figure below (Figure 6). The volumetric properties such bitumen content and average voids content of these mixes are summarized in Table 3. With regards to the results obtained from the CRT, the change in height in the wheel path, calculated using the data collected by a transversal profilometer, represents the average difference between the initial profile height and the profile height after a certain load passes. All slabs were 430 mm wide and only the central 300 mm have been considered in the analysis.

The SMA 11 standard in-situ and the SMA 8 standard are the ones primarily used in the Danish state network. The first is a terminal blend modified mixture while the second, reference mixture paved in Kalvehave, does not have any polymers. Both SMA8 COOEE+ and SMA6 COOEE+ have been produced using the same premodified bitumen and represents the mixtures paved in Kalvehave. The SMA8 COOEE+

Development and implementation of low rolling resistance pavement in Denmark

Table 3. Volumetric properties of the 5 asphalt mixes.

Name	Bitumen Type	Bitumen [%]	Av. Air Voids [%]
SMA 11 standard - "in-situ"	40/60+P-Flex	6.1	5.4
SMA 8 standard	70/100	6.9	5.5
SMA 8 COOEE+	40/100-75 EL	7.5	4.3
SMA 6 COOEE+	40/100-75 EL	8	6.8
SMA 8 COOEE+ - "in-situ"	70/100 + P-Flex	6.7	5.4

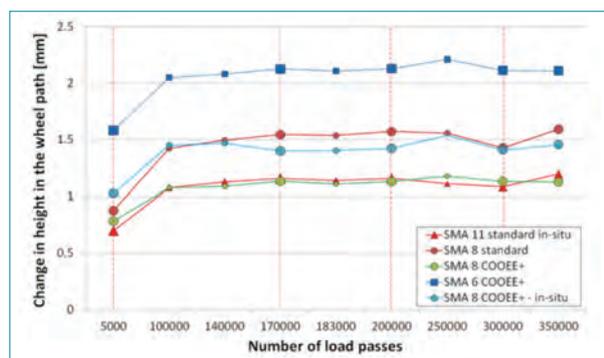


Figure 6: Development in wearing and rutting

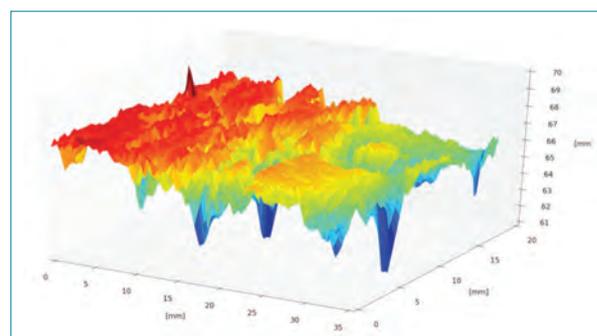


Figure 7: Example of 3D surface reconstruction based on the 2D texture measurements.

in-situ also contains polymers added during the asphalt mixture production.

The results represented in Figure 5 show that the SMA6 COOEE+ has the highest wearing depth even though most of it comes from the effect of the studded tyres. Both SMA 11 and SMA 8 COOEE+ are presenting the lowest wearing susceptibility.

4.2 Texture evolution

Another fundamental aspect of this investigation was the evaluation of texture and its changes due to different testing conditions. As described before, data analysis had also enabled the reconstruction of the 3D surface from the parallel longitudinal lines, as shown in Figure 7. The extrapolation of the 3D texture scan is still under investigation, even though the preliminary results seem promising, consequently only the study of the Mean Profile Depth (MPD) has been included. Finally, it should be noted that the MPD values might be a bit off in absolute values, but the relative comparison is unaffected, i.e., the relative order of the values is preserved. This is because the texture laser device has not been properly calibrated and the sampling resolution is quite high compared

to in-situ measurements on the road. Increasing sampling resolution is known to increase MPD.

For each measurement session, the parts of the data pertaining to each slab were identified and the MPD values were calculated for each slab [7]. There was a total of 9 measurement sessions and the results of these calculations are included in Figure 8, where the evolution of MPD is shown as a function of the number of cycles. The results summarized in Figure 8 show that after the first 5000 rounds with the studded tyres, all of the mixes exhibit a decrease in MPD until 200,000 cycles. During the winter simulation, a small increase in MPD has been detected even though only the one measured on the SMA11 standard can be considered significant. An interesting observation is how the different mixes react to the studded tyres which have been used during the first 5000 cycles. In fact during that test phase only the COOEE+ mixtures produced with premodified bitumen did not show any increase in MPD. It is not possible, based on the number of variables considered in this investigation, to make any statement about the reason why studded tyres had different effects on the different mixtures.

The order of the different slabs, with respect to the average MPD values, is in accordance with expectations. For instan-

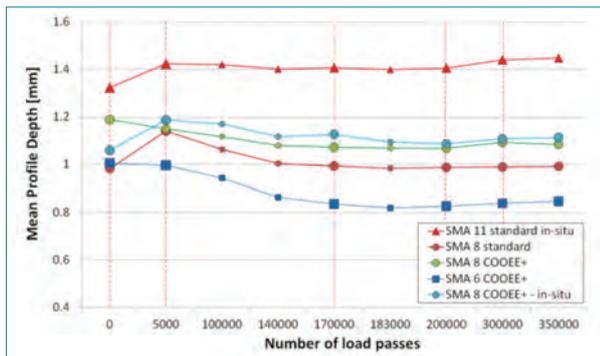


Figure 8: MPD values as function of cycles for each of the 5 mixes.

ce, the SMA 11 has by far the largest average MPD followed respectively by the different SMA 8 mixes and the SMA 6.

In general, there is a consistent texture-stability across all mixes and the relative order of magnitude of average texture values between the mixes is in accordance with the expectations. Of course, the use of studded tyres to simulated initial wear is not entirely realistic and the lack of chemical ageing might also have an effect.

5. Conclusions and next steps

The socio economic analyses of the COOEE+ pavement has shown that the implementation holds a particular beneficial potential and that the investment of implementing the COOEE+ pavement can be repeatedly shown to hold breakeven results within expected pavement life spans. It is essential that these low rolling resistance pavements proof a life time comparable to a conventional SMA11 and for this purpose the CRT has been performed. The CRT represents a reliable test device to study the behaviour of surface layers. Effect of temperature variation has been taken into account and the results were consistent. A relevant set of data have been collected during the entire test but further investigation of the data and collected pictures using image analysis should be performed.

In general the SMA 6 mixtures are worn more heavily by studded tyres than the other gradations mixtures. This was expected as wear from studded tyres depend predominantly on the nominal maximum aggregate size of the mix. Looking at the overall wearing and rutting performance, the SMA 8 COOEE+ and SMA 11 standard "in-situ" had similar performance. When wear from studded tyres is not taken into account, the SMA 8 COOEE+ shown lowest wearing susceptibility and highest texture stability.

The texture changes of the mixtures follow the expected trend where larger aggregate size results in rougher texture. It is difficult to say anything general about the different bitumen types from this test. Properly due to the fact that there is no significant chemical ageing during the test, the brittleness of aged bitumen did not come into play. It must be recognized that the tendency to use higher bitumen content might also lead into reduced texture deterioration.

6. References

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