Rutting potential and texture of thin asphalt layers

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ABSTRACT

Development and optimizing of mix design for thin asphalt surface layers with functional capabilities (i.e. noise reduction, low rolling resistance) is a laborious task with several loops from laboratory mix design to test section before a real progress can be achieved. To this end it will be highly advantageous if some screening of mix design can be performed in the laboratory which can indicate the path of development of optimal candidate mixes for full scale test sections for the final optimization.

Maintenance of existing infrastructure often calls for thin asphalt layers to provide the abovementioned functionalities on milled surfaces of old asphalt pavements. Decision of the thickness of the new asphalt layer can be a challenge due to the rough texture of the substrate. On one hand if the applied layer thickness is too high you may risk the occurrence of permanent deformations (rutting). On the other hand if the layer thickness is too small you risk poor durability.

This study evaluates the use of the texture profiles with high resolution laser measurements on laboratory compacted slabs of various thicknesses for Wheel Tracking Test with texture profiles of full scale pavements on a number of thin asphalt layers with functional capabilities.

Keywords: Compaction, Mixture design, Permanent Deformation, Stone Mastic Asphalt, Surface Texture

1. INTRODUCTION

1.1 Permanent deformations and wheel tracking test (WTT)

In the late 1980ties Denmark experienced an increasing problem of permanent deformation (rutting) on the road network. The cause was seen to be a combination of several factors. The traffic load was increasing and the population of trucks was changing. On the major road network the number of lorries with triple axles mounted with super single tyres increased rapidly in these years. The concentrated load in the wheel path made it evident, that especially the upper bituminous base (GAB 0) used on major roads had insufficient properties with respect to rutting resistance. The lack of "internal friction" in the material due to unsatisfactory amount of crushed aggregate indicated, that the mix design of the asphalt mixes normally used in Denmark in general could be improved with respect to resistance against permanent deformation.

The asphalt producers looked for new tools to help in the optimization of the asphalt mixes. Mix design had until then been based on the Marshall method combined with experience and in-house methods. While Sweden in a similar situation turned its attention to dynamic creep testing for functional contracts on rutting resistance, the Danish asphalt producers were more inclined to survey the different possibilities in Wheel tracking tests (WTT). The load conditions of the TRRL Wheel Tracking test [1] were found to be insufficient to distinguish between mixes, and the steel wheel of the original Hamburg Wheel Tracking test [2] showed the potential to crush aggregate particles or induce unrealistic high stresses in the contact points. Denmark decided to combine the load conditions from Hamburg with the rubber wheel from TRRL and succeeded in getting this combination standardized in the European standard as EN 12697-22 Model B (in water) [3].

The results of wheel tracking tests can be shown as curves of rut depth versus load cycles and have similar shapes as creep experiments and be divided up in three phases:

- Primary phase: initial setting of material (consolidation)
- Secondary phase: linear development of permanent deformation and
- Tertiary phase: acceleration of permanent deformation (flow).

Denmark has always preferred to perform the test in water (either 50 °C or 60 °C). An air bath is not equally efficient to control the temperature of the travelled path. Furthermore very lean asphalt mixes can show excellent rutting resistance when tested dry but will fail miserably under moist or wet conditions in the field. If WTT is performed in a water bath, lean mixes can demonstrate a transition from the secondary to tertiary phase, which is not related to permanent deformation but is the result of stripping and deterioration of the material. Many countries prefer to use EN 12697-22 Model B (in air) in order to avoid false interpretation of this as permanent deformation. The Danish position is: if the material shows tertiary flow or a stripping inflection point within the first 10,000 load cycles the material has failed to be used in the wet or moist climatic conditions in Denmark. Additional information on the water sensitivity of the mix has been gained by performing the test in water in the mix design process [4].

1.2 Thin asphalt layers and texture

Denmark has been involved in research on thin asphalt surface layers for more than a decade for their capability to reduce the noise emission from the tyre-road interaction. This has resulted in a trend towards smaller nominal maximum aggregate size (NMAS) and a desire to assess the surface texture in relationship to both noise and friction (skid resistance). Recently Danish Road Directorate built equipment for detailed texture measurements by mounting a high resolution laser on a transportable beam. This gave the option to measure x-z profiles in the laboratory on smaller spe-

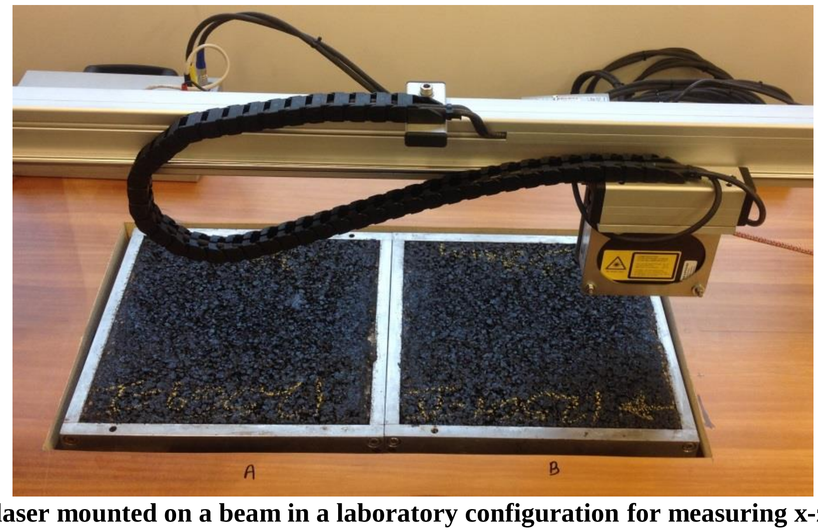

Figure 1 Texture laser mounted on a beam in a laboratory configuration for measuring x-z texture profiles on roller compacted asphalt slabs before Wheel Tracking Test (WTT) according to EN 12697-22

cimens and profiles out on test sections in the field with length up till 1.5 m using the same software for signal analysis and reporting [5]. One of the reasons for development of this equipment for laboratory purpose is to explore relationships between surface texture and noise reducing capability in order to facilitate further optimization of mix design before actual field tests are performed. But for this purpose the “quality” (e.g. reproducibility) and dependencies of various parameters of laboratory compaction need to be assessed.

2. OBJECTIVE OF THE STUDY

There exists a rule of thumb, which states, that the optimum layer thickness of an asphalt material is 2.5 – 4.0 x the nominal maximum aggregate size. Below 2.5 you risk poor compaction and above 4.0 you risk permanent deformation. Due to the trend of decreasing the nominal maximum aggregate size of the thin noise reducing surface layer it is allegedly imposing a potential risk of permanent deformation. This has been further emphasized as the road administration has shown an interest to increasing the layer thickness of the surface layers – especially for rehabilitation of milled (coarse milled) surfaces – in order to improve a challenged durability.

The objectives of this study are

- To examine the influence of layer thickness on the potential of permanent deformation beyond a factor 4.0 with respect to the nominal maximum aggregate size and
- To evaluate the influence from production of laboratory compacted slabs of various layer thicknesses by the initial texture profiles of the slabs and
- To answer if initial texture profiles on laboratory produced sample show potential as an optimization tool to reduce the number of necessary field test sections.

In a later stage of the project an objective is to compare the initial texture profiles of laboratory compacted slabs with texture profiles of full scale pavements on a number of thin asphalt layers with functional capabilities.

3. MATERIALS AND TEST CONDITIONS

The three asphalt materials in this study are plant produced mix which have been sampled, cooled and later reheated for compaction of the slabs. The mix design of the three materials originates from the Stone Mastic Asphalt (SMA) family (EN 13108-5) and has been optimized further for noise reduction or low rolling resistance. The nominal maximum aggregate size (NMAS) is either 6 or 8 mm. They are all polymer modified asphalt which means the polymer addition is happening “in-situ” in the pug mill of the asphalt batch plant. The level of polymer modification aims for an expected softening point ring and ball of the resulting binder of less than 55 °C which according to the Danish guideline for WTT set the conditions as EN 12697-22 Model B in water at 50 °C.

The compaction device is equipped with a segment of the smooth steel drum roller. A thin sheet of silicone impregnated paper has been used between the roller segment and the hot asphalt, and the paper was removed immediately after the compaction was accomplished. Different spacers have been used in the roller compaction device, and two slabs have been produced of each asphalt and layer thickness (29, 38 and 58 mm). The slabs are square-shaped with a side length of 305 mm. The target for the compaction degree has been 97.5 % (relative to the Marshall specimen from the producer’s specification).

All samples have been stored at ambient temperature for 8 days before WTT. During this period the x-z profiles have been measured. After reaching equilibrium at the test temperature the samples have been subjected to 10,000 load cycles during the WTT. The rut depth has been determined at the midpoint of wheel travel for each load cycle until 100 and for every 100th load cycle until 10,000. The data point from 100 to 10,000 load cycles have been fitted to a power function of rut depth (Y) versus load cycles (X) with the following equation:

$$\boldsymbol{Y = AX^B}$$

Texture beam equipment has the capability of measuring an x-z profile with a resolution of 8.75 micron in the z-direction for each increment of 0.18 mm in the x-direction. Six x-z profiles were measured, as depicted in Figure 2; three in the direction of the compaction and three perpendiculars to it. The three parallel profiles were measured at the centreline and ± 50 mm from it.

From each profile with a potential length of 305 mm the mid approx. 276 mm was analysed after subdivision into three sections of 91.98 mm. This peculiar length was caused by the intent to use the texture measurements of the sections for another project where Fast Fourier Transform filtering would be used. In order to accommodate the FFT filtering the number of sample points shall be a multiple of 2 to the power of x. The increments of 512 sample points (2^9) give a distance of 91.98 mm. The x-z profile of each section has been averaged and subjected to slope suppression to create a normalised z-profile. An example of a normalised z-profile is shown in Figure 3.

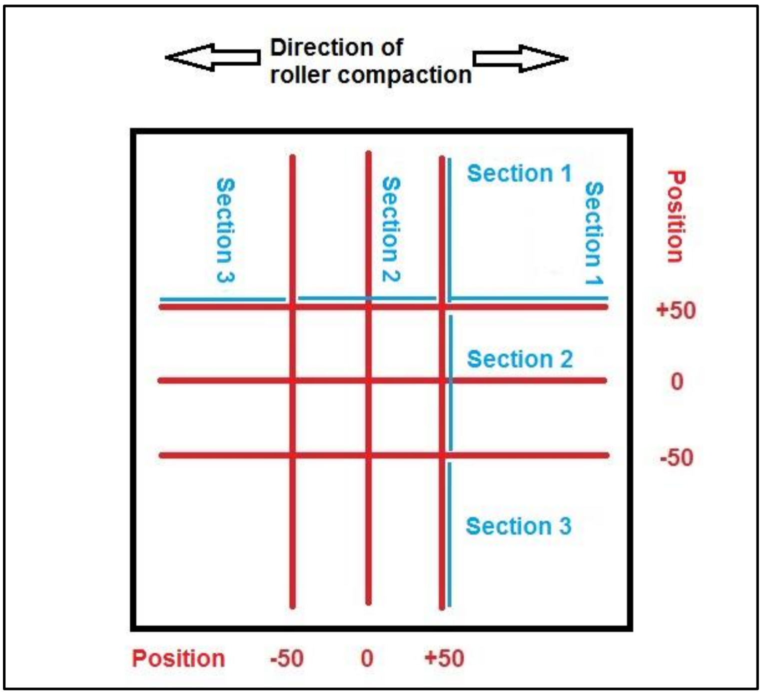

Figure 2 Schematic placement of the six measured x-z texture profiles on a slab; each subdivided in three sections.

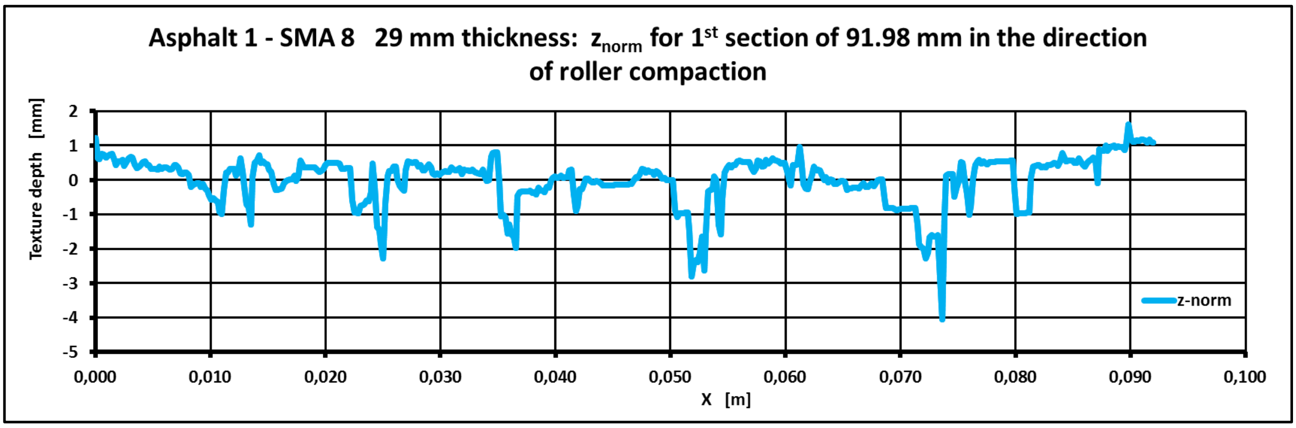

Figure 3 Example of normalised z-profile (beware of the different scales on the axes)

4. RUTTING POTENTIAL OF THIN ASPHALT LAYERS

4.1 Results of Wheel Tracking tests

The results of the 18 slabs are depicted in Figure 4. Table 1 contains the characteristic of the slabs, the measured density and the resulting compaction degrees with some variation from the intended 97.5 %. Three set of slabs achieved a lower compaction degree at production which can be explained by a set of 21 mm spacers having a smaller height than anticipated. The table shows also the coefficients of the fitted power function and the correlation coefficient, R^2, together with the measured rut depths after 5,000 and 10,000 load cycles and the Wheel Tracking Rate (WTR).

Analysis of Variance (ANOVA) has been performed on the data from Table 1 with respect to the factors Asphalt and Layer thickness, since a preliminary analysis showed, that the factor Slab (production sequence) had no influence on the results.

The level of influence is judged by the probability, P, for rejection of the null hypothesis. The following expression will be used for the level of influence in this paper:

- Strong significant $P \le 0.001$
- Significant $0.001 \le P < 0.010$
- Weak significant $0.010 \le P < 0.050$

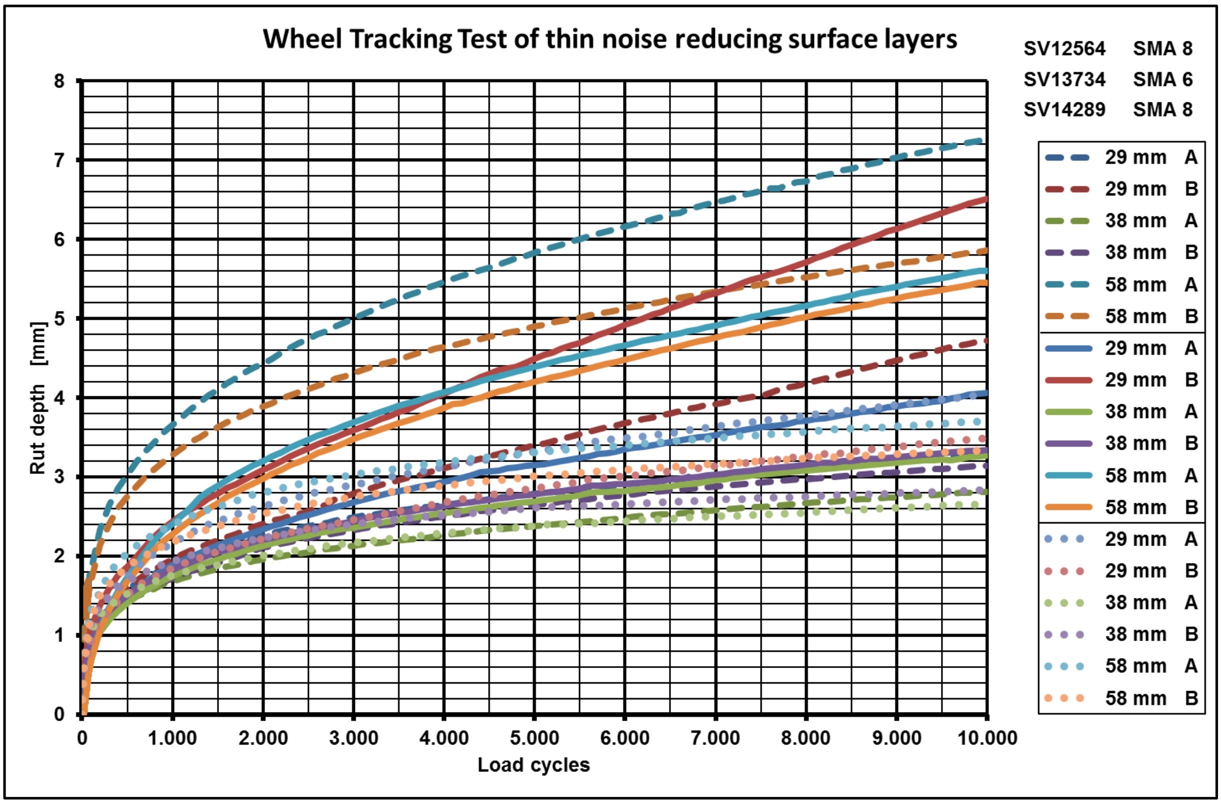

Figure 4 Rut depth versus load cycles for the various asphalt materials and layer thicknesses.

Table 1 Sample data and coefficients and correlations for the power function $Y = AX^B$ for rut depth versus load cycles from 100 – 10,000 in addition to measured rut depth after 5,000 and 10,000 load cycles and the Wheel Tracking Rate (WTR).

Asphalt	NMAS	Layer thick-ness	Density	Compac-tion degree	A (factor)	B (exponent)	Correlation R^2	D_5000	D_10000	WTR
ID No.	mm	mm	Mg/m^3	%	mm			mm	mm	mm/1000
SV12564	8	29	2.307	97.3	0.3255	0.2521	0.9926	2.79	3.28	0.098
			2.289	96.5	0.1608	0.3607	0.9907	3.40	4.72	0.264
		38	2.323	98.0	0.3215	0.2358	0.9937	2.38	2.81	0.086
			2.282	96.2	0.2699	0.2678	0.9977	2.65	3.14	0.098
		58	2.225	93.9	0.4829	0.2931	0.9991	5.83	7.27	0.288
			2.227	93.9	0.5564	0.2556	0.9989	4.90	5.86	0.192
SV13734	6	29	2.289	96.0	0.2048	0.3218	0.9987	3.15	4.06	0.182
			2.276	95.5	0.1507	0.4018	0.9897	4.49	6.51	0.404
		38	2.330	97.7	0.2437	0.2826	0.9970	2.69	3.27	0.116
			2.339	98.1	0.2863	0.2672	0.9987	2.78	3.34	0.112
		58	2.256	94.6	0.1480	0.3978	0.9864	4.39	5.60	0.242
			2.252	94.5	0.1351	0.4035	0.9937	4.20	5.45	0.250
SV14289	8	29	2.243	95.4	0.3194	0.2753	0.9983	3.32	4.04	0.144
			2.244	95.5	0.2774	0.2740	0.9993	2.86	3.49	0.126
		38	2.297	97.8	0.4772	0.1877	0.9956	2.39	2.65	0.053
			2.293	97.6	0.5587	0.1793	0.9846	2.62	2.85	0.047
		58	2.276	96.9	0.5749	0.2047	0.9869	3.31	3.70	0.078
			2.278	96.9	0.5420	0.2001	0.9887	3.01	3.34	0.066

Rut depths after 5,000 load cycles (D_5000) and 10,000 load cycles (D_10000) are strong significantly (Probability P = 0.0019) respectively significantly (P = 0.0046) influenced by the factor Layer thickness. If the Compaction degree is taken into account as covariant, the influence from the layer thickness disappears. D_10000 is almost weak significantly influenced by the factor Asphalt, but this disappears also when Compaction degree is used as covariant.

The ANOVA of Wheel Tracking Rate (the slope of rut depth between 5,000 and 10,000 load cycles) is weak significantly influenced by both Asphalt and Layer thickness with respectively (P = 0.0151) and (P = 0.0205). The influence of Layer thickness disappears when Compaction degree is used as covariant, but the influence of Asphalt remains on a weak level of significance (P = 0.0307).

5. TEXTURE OF THIN ASPHALT LAYERS

5.1 Results of the texture measurements

It is appropriate to recall, that the texture measurements have been performed on laboratory compacted slabs of asphalt which have not been worn by traffic, yet. The initial mortar is still intact on the surface of the slabs. It would have been pointless to measure to texture of the travelled path after the WTT, since the load conditions vary over the total length (due to sinusoidal speed variations), and the rubber wheel does not have the same “mortar removal” capability as normal traffic anyway.

From the normalized z-profiles of the individual sections numerous characteristic parameters can be calculated:

- Variance Sample variance of the section
- Std_dev Sample standard deviation of the section
- Min Minimum value of the section
- Max Maximum value of the section
- Range Difference from minimum to maximum value.
- Skewness Skewness of z-profile of the section
- Kurtosis Kurtosis (momentum) of the z-profile of the section
- Z_RMS Power value (Root-Mean-Square-value) of the section
- Quantile_x The x %- quantile of the z-profile of the section

The data allows for six factors to be analysed by the ANOVA:

- Factor A. Asphalt (SV12564 SMA 8, SV13734 SMA 6 and SV14289 SMA 8)
- Factor B: Slab (first or second produced slab)
- Factor C: Layer thickness (29, 38 and 58 mm)
- Factor D: Section (subsection 1, 2 and 3)
- Factor E: Position (with respect to centreline)
- Factor F: Direction of roller compaction (0° or 90°)

Compaction degree is not considered in the analysis of the texture, since this parameter only show minor deviation from the intended value and because of this it is not envisaged to have the same influence on the texture as on the permanent deformation properties by the WTT measurements. The six-ways ANOVA is analysed for 1st order effects and 2nd order interactions of the factors and the result can be seen in Table 2.

It is no surprise, that the factor Asphalt has a significant or strong significant effect on most of the parameters in Table 1. But it is interesting, that the factor Layer thickness has an equal or even stronger effect on the surface texture of the samples. Both factors participate in 2nd order interaction among each other with weak significant influence for several parameters and especially Layer thickness appears frequently in 2nd order interactions with other factors like Slab and Section.

On the other hand it is a little astonishing, that the factor Direction of roller compaction does not show up as 1st order effect and just participate in three weakly significant 2nd order interactions with other factors Slab, Layer thickness and Section. There is also no interaction between Asphalt and Direction of roller compaction.

Even after averaging and slope suppression of the x-z profiles of the sections it is possible to see a few significant effects of the factor Position and a few weakly significant effects and interactions from the factor Section towards other factors. This can be interpreted as the roller compaction with a drum segment can create an overall s-shaped profile in the z-direction over the compaction form length of 305 mm, but with a wave length, that is very long compared to the NMAS of the asphalt.

Table 2 Result of six-ways ANOVA on various parameters of the normalized z-profiles (texture) given by the letters representing the variables or interactions with the probability value, P, for no influence.

Legend:

- **Factor A: Asphalt**
- **Factor B: Slab**
- **Factor C: Layer thickness**
- **Factor D: Section**
- **Factor E: Position**
- **Factor F: Direction of compaction**

Parameter	Strongly significant effect	Significant effect	Weakly significant effect
Variance	C (P = 0.0000) A (P = 0.0003)		E (P = 0.0171) AC (P = 0.0219) BC (P = 0.0377) D (P = 0.0451)
Std_dev	C (P = 0.0000) A (P = 0.0000)	E (P = 0.0094)	BC (P = 0.0154) AC (P = 0.0207) D (P = 0.0391)
Min	A (P = 0.0000) C (P = 0.0006)		DE (P = 0.0467)
Max	A (P = 0.0000) C (P = 0.0000)	DE (P = 0.0043) E (P = 0.0093)	D (P = 0.0101) AC (P = 0.0414) BC (P = 0.0450)
Range	A (P = 0.0000) C (P = 0.0000)	DE (P = 0.0052)	E (P = 0.0216) AD (P = 0.0239) AC (P = 0.0288)
Skewness			CE (P = 0.0290)
Kurtosis			A (P = 0.0162)
Z_RMS	C (P = 0.0000) A (P = 0.0000)	E (P = 0.0094)	BC (P = 0.0154) AC (P = 0.0207)
Quantile_01	C (P = 0.0000)	A (P = 0.0060)	
Quantile_05	C (P = 0.0000)	A (P = 0.0053)	E (P = 0.0334) BF (P = 0.0353)
Quantile_10	C (P = 0.0000) A (P = 0.0006)	BC (P = 0.0068)	CD (P = 0.0384) AC (P = 0.0439)
Quantile_25	A (P = 0.0000) C (P = 0.0001)	BE (P = 0.0032) B (P = 0.0053)	AC (P = 0.0105) E (P = 0.0199) CF (P = 0.0207) CD (P = 0.0396)
Quantile_50 (median)			A (P = 0.0135) C (P = 0.0165)
Quantile_75	C (P = 0.0000) A (P = 0.0001)		AC (P = 0.0203)
Quantile_90	C (P = 0.0000) A (P = 0.0001)	AC (P = 0.0020)	D (P = 0.0493)
Quantile_95	C (P = 0.0000) A (P = 0.0000)	BC (P = 0.0045)	E (P = 0.0289)
Quantile_99	C (P = 0.0000) A (P = 0.0000)		E (P = 0.0111) CD (P = 0.0329) DF (P = 0.0385) BC (P = 0.0391) AC (P = 0.0399)

6. CONCLUSIONS

6.1 Rutting potential in relation to layer thickness and NMAS

A rule of thumb says that the optimal layer thickness shall be less than 4 times the nominal maximum aggregate size (NMAS) in order to avoid risk of permanent deformation. The objective has been to indicate the influence of layer thickness and NMAS on rutting and surface texture on laboratory-compacted specimens.

The back ground for the conclusions is, that it is a study with a limited number of samples. The three surface layer asphalt materials are not randomly chosen but developed for noise reduction or low rolling resistance and have during their development also been optimized for rutting resistance.

Permanent deformation in WTT after EN 12697-22 Model B (in water):

1. The Analysis of Variance (ANOVA) shows, that the layer thickness has a significant influence on the deformation after 5,000 load cycles, but when the measured compaction degree is used as covariant the influence of layer thickness disappears.
2. The ANOVA shows, that
    - The layer thickness has a significant influence and
    - The asphalt has almost a weakly significant influence (P = 0.0533) on the deformation after 10,000 load cycles. If the measured compaction degree is used as covariant the influence from both factors disappears.
3. The ANOVA shows, that both layer thickness and asphalt have a weakly significant influence on Wheel Tracking Rate (WTR, slope of permanent deformation between 5,000 and 10,000 load cycles). If the measured compaction degree is used as covariant it is only the asphalt, which remains to have a weakly significant influence on the Wheel Tracking Rate.
4. The test results indicate that the three asphalt materials with NMAS of 6 and 8 mm can be paved in well compacted layer thicknesses larger than "4.0 x NMAS" without additional risks for rutting under the tested conditions (50 °C).

6.2 Texture profiles of laboratory-compacted specimens in relation to layer thickness and slab production

It must be recognized in evaluation of the measured texture profiles, that the surface of the laboratory-compacted slabs are still covered by the bituminous mortar which under real conditions on the road will be worn off/disappear during the first months under normal traffic.

Texture-profiles (normalized subsections i.e. after averaging and subjection to slope suppression):

1. It is assumed – from a visual inspection –, that the texture of the surface of the asphalt slabs is not influenced by the small variations in compaction degree (in contradiction to the situation with the mechanical loaded wheel tracking tests).
2. The examined texture profiles of the three asphalt surfaces show, that the texture is convex since the median (50 % quantile) for all texture profiles arte larger than 0 mm.
3. The 6-way Analysis of Variance is performed for the following factors:
    - Asphalt material (three noise reducing or low rolling resistance surface layers)
    - Slab (first or second produced slab)
    - Layer thickness (29, 38 and 58 mm)
    - Section (subsection 1, 2 and 3)
    - Position (centerline or ± 50 mm)
    - Direction of roller compaction (0° or 90°)
4. Asphalt and layer thickness have a strongly significant influence on the following parameters for the normalized texture profiles:
    - Sample variance of the section
    - Sample standard deviation of the section
    - Minimum value of the section
    - Maximum value of the section
    - Difference from minimum to maximum value.
5. Asphalt and layer thickness have a (predominantly) strongly significant influence on the following quantiles of the normalized texture profiles:
    - 1 %, 5 %, 10 %, 25 %, 75 %, 90 %, 95 % and 99 %
    - On the median (50 % quantile) just a weakly significant influence.
6. The Root-Mean-Square value of the texture profiles is significantly influenced by asphalt material, layer thickness and the position of the profile relative to the centerline.
7. Skewness and kurtosis are not very important as characteristics of the texture profiles. Skewness is weak significantly influenced by an interaction between layer thickness and position while kurtosis is weak significantly influenced by asphalt material.

8. Several (primarily weak) interactions among the examined factors have been found, that indicate, that the distribution of the loose asphalt in the mould prior to compaction has an influence on the obtained texture.
9. It is noteworthy, that the texture is strong significantly influenced by the layer thickness, but there is no effect from the direction of roller compaction on the texture.

6.3 In summary:

The results indicate with reference to the rule of thumb, that if the asphalt is optimized for rutting resistance there is limited risk of permanent deformation in paving the asphalt in layer thicknesses up till 7 times the nominal maximum aggregate size (NMAS).

Distribution of asphalt materials in the Wheel Tracking Test mould prior to compaction and the compaction process in itself needs more consideration before the surfaces texture of laboratory-compacted specimens can be correlated to texture of field performance.

Several parameters for description of surface texture profiles of laboratory compacted asphalt slab are significantly influenced by the layer thickness in the range of 29 - 58 mm. This imply, that transversal and longitudinal variations in layer thickness can have similar effect on surface texture profiles of in full scale pavement and add to the bias of texture inventory measurements.

7. ACKNOWLEDGEMENTS

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