Additional knowledge of low temperature behavior of asphalt characterized by maximum indirect tensile strength reserve

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ABSTRACT

The maximum indirect tensile strength reserve is currently an important parameter to describe the low temperature behavior of asphalt. It describes the tensile strength of asphalt in consideration of traffic loading and cryogenic tension. The combination of Uniaxial Tension Stress Tests (UTST) and Thermal Stress Retained Specimen Tests (TSRST) is used for experimental determination of this feature. Specimens can be core samples or specimens produced in the laboratory.
Practice shows that minor deviation in mixtures, even by complying all tolerances, can have a direct influence on performance-features. In addition to this the influence on performance-features of mixture production (in laboratory or at mixing plant) and different production of test specimens (prepared by roller compactor or in situ compacted cores) are not described sufficiently. The project FE 07.0253/2011/ERB "Representative Determination of Performance-relevant Asphalt Properties that Provide the Basis for New Conditions of Contract", which is in the process of being completed, recorded and evaluated these influences on low temperature behavior of asphalt.
Thereby correlations between performance-features of mixtures, produced during initial type testing or at a mixing plant and core samples need to be found. Afterwards it will be possible to indicate the low temperature behavior of the paved course at the time of initial type testing.

Keywords: Asphalt, Low-Temperature, Performance testing

1. INTRODUCTION

The environmental impact of temperature has a high influence on asphalt pavements. Based on the temperature depending properties of asphalt and its components (aggregates and bitumen), thermal strain will occur in the construction as a result of temperature cooling. The low temperature impact is an important issue for road construction, because it leads to cracking in connection with heavy traffic loading. Due to increasing traffic loading and extreme cold periods, the low temperature behavior of asphalt needs to be precisely investigated.
The harmonized European asphalt specification introduced testing methods which enable to evaluate asphalt performance in the laboratory. The behavior in use of asphalt can be identified by means of testing methods described in parts of standard DIN EN 12697 "Test methods for hot mix asphalt". To describe the low temperature behavior of asphalt, part 46 of DIN EN 12697 can be used: "Low temperature cracking and properties by uniaxial tension tests" [1]. The maximum indirect tensile strength reserve, a parameter to estimate bearable traffic loading in connection with low temperatures, is currently an important parameter to describe the low temperature behavior of asphalt. It describes the tensile strength of asphalt in consideration of traffic loading and cryogenic tension. The combination of Uniaxial Tension Stress Tests (UTST) and Thermal Stress Restrained Specimen Tests (TSRST) is used for experimental determination of this feature [5].
The determination of low temperature behavior of asphalt with the above named testing methods can be carried out by using laboratory-manufactured specimens or specimens obtained from drill cores. Asphalt mixtures for laboratory-manufactured samples can also either be produced in the laboratory or industrially in an asphalt mixing plant. In addition to this the influence on performance-features of mixture production and different manufacturing methods of specimens (prepared by roller compactor or in situ compacted cores) are not described sufficiently.
Practice shows that minor deviation in mixtures, even by complying all tolerances in accordance with the technical guidelines, can have a direct influence on performance-features. Actually there is no detailed knowledge of possible differences and changes in the behavior in use of laboratory-manufactured asphalts or the behavior of the in-situ installed asphalt layers. So far, no statement can be made about the effects resulting for the calculated dimensions or for the reproducibility of the parameters determined by means of performance testing methods within quality assurance processes.
The research project "Representative Determination of Performance-relevant Asphalt Properties that Provide the Basis for New Conditions of Contract" funded by the German Federal Ministry of Transport, Building and Urban Development [6] recorded and evaluated the influences of the different production stages on low temperature behavior of asphalt and describes the correlations between performance-features of mixtures produced during initial type testing or at a mixing plant and core samples. The results of the performance tests concerning the low temperature behavior of asphalt surfaces will be discussed here.

2. DATABASE

21 sections were analyzed in this project to establish basic principles for drawing up conditions of contract that are based on performance tests. For that purpose performance parameters during initial type testing (stage EP) and production in a mixing plant (stage MW) as well as after asphalt paving (stage BK) were systematically determined and evaluated for the asphalt surfaces, binders and base layers. Each section was therefore sampled at three different stages of investigation (figure 1).
Stage 1 (EP) is related to asphalt mixture design with "reconstruction" of the initial type testing. If known, bitumen of the same producer, which was also used for initial type testing was used for "reconstruction". That procedure was chosen to display practice. If bitumen producer according to initial type testing could not be named, the bitumen used at stage MW was gained from the same fabricator and used for "reconstruction". Stage 2 (MW) investigates industrial-scale asphalt mixture production by examining the asphalt mixture produced at the asphalt mixing plant. Stage 3 (BK) represents the paved asphalt layer. Drill cores with different diameters for the single performance tests were sampled shortly after paving at the same spot where asphalt mixture samples for investigations within stage 2 had been taken.
This also means that all three stages differ from each other concerning the type of mixing and/or type of compaction. Stage EP also may vary from stages MW and BK concerning bitumen producer. Stage BK and MW are mixed in an asphalt mixing plant, stage EP is mixed in small scale at the laboratory. Stage BK is compacted in situ, the specimens of stages MW and EP are roller compacted in the laboratory, except for section 15 which consists of mastic asphalt and is accordingly prepared in the laboratory.
Due to the fact that the differences between these three production stages were main objectives to identify, a great variety of asphalt mixture types according to different initial type testings could be considered.

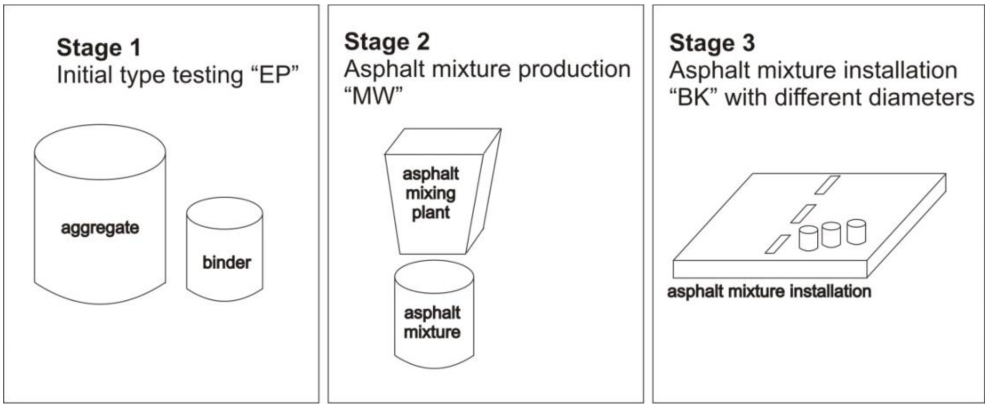


Figure 1: Stages of investigation

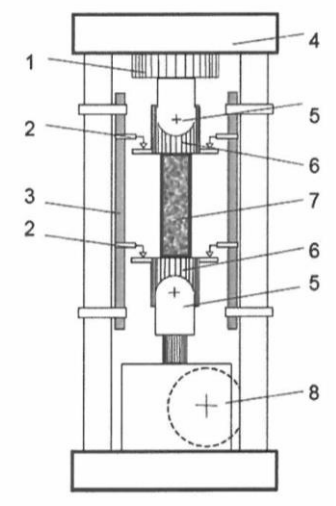
The investigation included 16 stone mastic asphalts (9x SMA 8 S, 5x SMA 11 S, 2x SMA 8 LA), four asphalt concretes (3x AC 11 D S, 1x AC 11 D N) and one mastic asphalt (MA 5 S) for asphalt surfaces. Table 1 gives an overview of the analyzed asphalt mixtures and the used bitumen or resulting bitumen if asphalt granulates were added to the mixture.
The Thermal Stress Restrained Specimen Test as well as the Uniaxial Tension Stress Test were performed to determine the low-temperature flexibility of the 21 different asphalt mixtures at each stage. In addition to this conventional properties of asphalt composition like granulometry, bitumen content, density and compaction ratio as well as conventional and performance-related bitumen features were identified. For possible future performance based contract conditions it is necessary to forecast performance parameters of the paved layers by known parameters evaluated in the laboratory at stage EP. So this project is intended to create a prognosis to evaluate performance properties at stage BK based on the properties determined at stage EP.

Table 1: Overview of the analyzed asphalt mixtures and the resulting bitumen

section no.	asphalt	(res.) bitumen	section no.	asphalt	(res.) bitumen
1	SMA 11 S	25/55-55 A	12	SMA 8 S	25/55-55 A
2	AC 11 D N	50/70	13	SMA 8 S	25/55-55 A
3	SMA 8 S	PmB NV 45	14	AC 11 D S	25/55-55 A
4	SMA 8 S	PmB NV 45	15	MA 5 S	20/30
5	SMA 11 S	25/55-55 A	16	SMA 11 S	25/55-55 A
6	SMA 8 LA	40/100-65 A	17	SMA 11 S	25/55-55 A
7	AC 11 D S	25/55-55 A	18	SMA 11 S	25/55-55 A
8	SMA 8 S	25/55-55 A	19	SMA 8 S	25/55-55 A
9	SMA 8 S	25/55-55 A	20	SMA 8 S	25/55-55 A
10	AC 11 D S	25/55-55 A	21	SMA 8 LA	40/100-65 A
11	SMA 8 S	25/55-55 A			

3. TEST METHODS

To determine low temperature behavior of asphalt mixtures, a combination of Uniaxial Tension Stress Tests (UTST) and Thermal Stress Restrained Specimen Tests (TSRST) is used [5]. Figure 2 shows the test set-up to analyze the low temperature behavior. Specimens can be core samples or specimens produced in the laboratory.



1 Load Cell
2 Displacement Transducer
3 Thermal Indifferent Measurement Base
4 Crossbeam
5 Gimbal suspension
6 Adapter
7 Test Specimen
8 Gear box with stepping motor

Figure 2: Test set-up to perform TSRST and UTST

In the TSRST the specimen is held in constant length, while test temperature is constantly reduced, starting at 20 °C with a constant cooling rate of -10 K/h. Meanwhile the thermal-shrinkage of the specimen is retained due to the constant length of the specimen. Therefore thermal stress is applied by temperature cooling and cryogenic tensile stress is arising which leads to low temperature cracking, when cryogenic tensile stress reaches its maximum. The test is stopped as soon as the specimen fractures. Failure stress and failure temperature represent the important parameters of this test. The process of the rising cryogenic tensile strength is shown in figure 3 (blue line).
In the Uniaxial Tensile Stress Test (UTST) the specimen experiences a standard deformation rate of 1 mm/min by a constant test temperature, which is set to +20, +5, -10 or -25 °C. Due to the increasing deformation the tensile stress is arising in the specimen. The test ends as soon as fracture occurs. The test results are tensile strength and the failure strain at each test temperature. Based on the tensile strength of the four test temperatures, the tensile strength curve depending on temperature can be interpolated by using a cubic spline function. This curve is shown in figure 3 (red line).
To determine the maximum tensile strength reserve, key material parameter to characterize low temperature behavior, the tensile strength and the cryogenic stress are combined in a stress-temperature-diagram. The tensile strength reserve results as the difference of the tensile strength and the cryogenic tensile stress (figure 3, black line). The maximum of this curve is the maximum tensile strength reserve with its associated temperature.

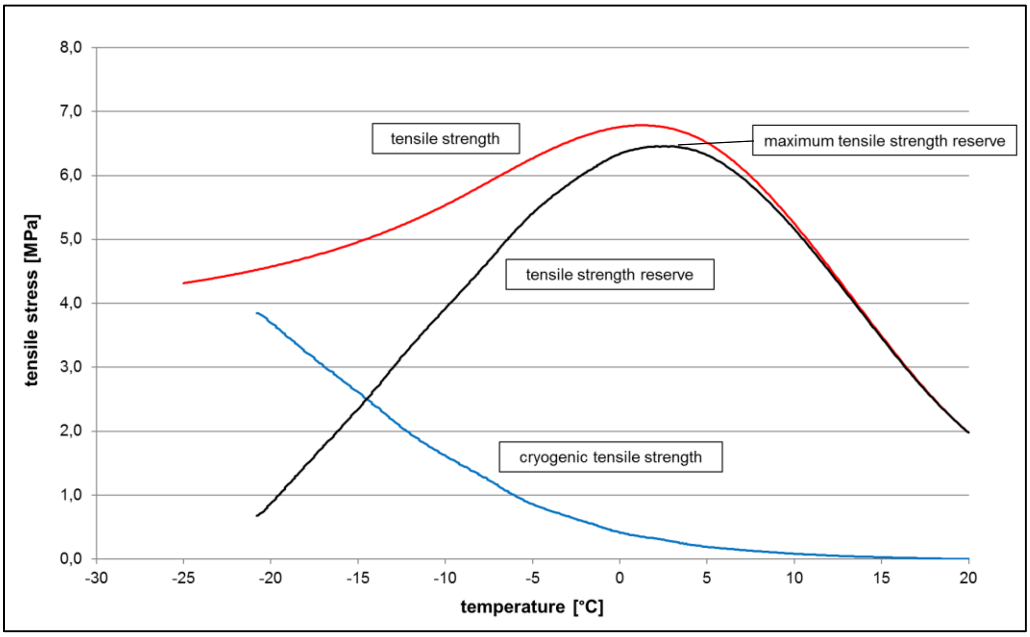


Figure 3: Typical results of TSRST (blue), UTST (red) and tensile strength reserve (black)

4. LOW TEMPERATURE BEHAVIOR OF ASPHALT AT DIFFERENT PRODUCTION STAGES

4.1 Thermal Stress Restrained Specimen Test

In figure 4 and 5 the results of the TSRST (failure temperature and failure stress) at the three stages of all investigated sections are sorted by asphalt and bitumen type.

Altogether seven times a SMA 8 S with 25/55-55 A was examined and stages MW and BK show on average a failure temperature of -24 °C. In contrast to this the average failure temperature of stage EP is about 2 K higher. The sections no. 13 and 19 are the only ones, which reach deeper failure temperatures at stage EP than at the other two stages. The conspicuity of section no. 19 can be found in the hardening of the bitumen during mixing process, which is shown in a decreased value of needle penetration at stage MW (MW: 2,5; BK: 3,1; EP: 3,8 mm). Section no. 13 does not show conspicuities on binder viscosity, which could lead to a higher failure temperature at stage MW. Section no. 20 shows a very high level of failure temperature at all stages, which may result from the 30 % of asphalt granulates and consequently a hardened asphalt mixture. On the other hand stage BK shows generally lower failure stress and stages EP and MW extend to higher stress, which is partly on a similar level. The statistical evaluation of SMA 8 S shows no differences in failure stress between the stages EP and MW except for two sections (no. 12 and 19) and no statistical difference between the stages MW and BK in failure temperature (except for no. 11 and 19).

The samples of sections no. 3 and 4 (SMA 8 S with PmB 45 NV) were taken at a distance of 500 meter. The samples are from different production charges and also vary in the type of bitumen used during initial type testing at stage EP. Even though the same material was examined, the failure temperature of these two drifts vary at stage MW around 1,7 K and at stage BK around 1,5 K. The failure stress varies at stage MW only around 0,3 MPa and at stage BK around 0,2 MPa. These differences are still inside the repeatability limit of the DIN EN 12697-46 [1].

The SMA 11 S was used in five sections. There is no consistent ranking of failure temperatures between the stages and the greatest differences between the stages EP and BK encounter in section no. 17 with 4,4 K and in no. 18 with 3,6 K. However stage MW reaches always higher failure stress than stage BK in these five sections. In four sections this is also the case at stage EP. Furthermore the statistical analysis show that the three stages display no statistical differences except for section no. 17, in which stage EP has a significantly higher failure temperature. In three of five cases significant differences in failure stress are determined and it is stage BK, which shows significant differences from stage MW.

All three analyzed AC 11 D S show the lowest failure temperature and failure stress at stage BK. Nevertheless there are in two of three cases no statistical differences detected between the three stages in failure temperature and failure stress.

The two investigated noise optimized SMA 8 LA show no consistent ranking between the stages, apart from stage BK reaching deeper failure temperatures and lower failure stress than stage EP. The statistical evaluation shows no consistent outcome.

AC 11 D N and MA 5 S were just examined in one section, so there is no statistical statement to be made.

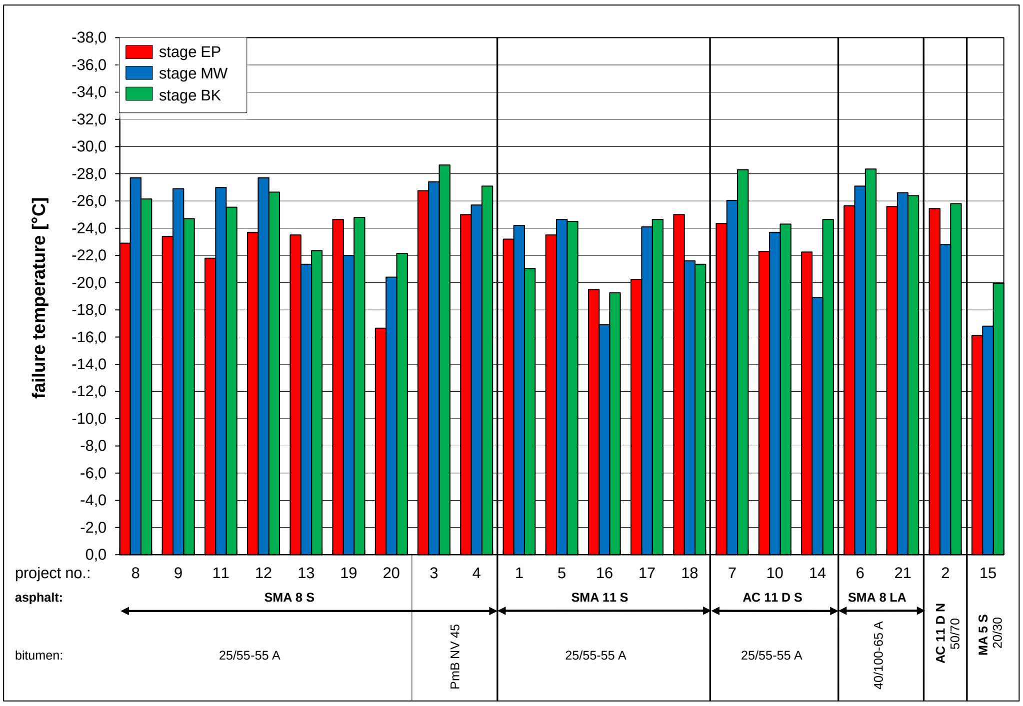


Figure 4: Failure temperatures of the 21 sections at the three stages

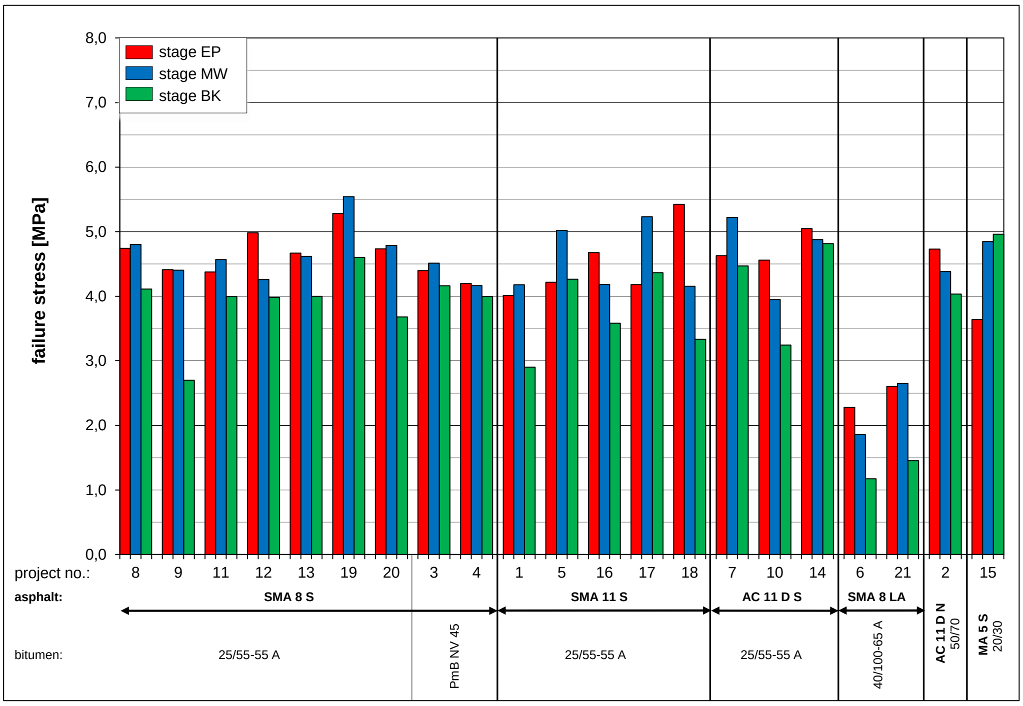


Figure 5: Failure stress of the 21 sections at the three stages

From the research it did appear that even by looking at one asphalt type, there are great spans and no regular ranking of low temperature values between the three stages has been found. But in summary 13 of the 21 sections don't show a statistically significant difference in failure temperature between the stages within one section. If differences were shown, stage EP reaches higher failure temperature and stage BK reaches, partly on a similar level with stage MW, the deepest failure temperature. Stage MW varies in most cases around ±3,0 K from stage BK. Failure stress shows in eight times no statistical differences between the stages and stages EP and MW display mostly higher failure stress than stage BK. It also turned out, that conspicuities in failure stress are not necessarily displayed in failure temperature. Stage BK shows in general the lowest failure stress, while stages EP and MW are partly on a similar, higher level. In this connection the influence of the manufacturing method of the specimens (from drill cores or from roller compactor) is clearly visible. It was also examined, if conspicuities in conventional asphalt properties (density, granulometry, bitumen content and compaction ratio) exist, no relation was found in connection with performance features.
Stage EP represents a composition according to the specifications of the initial type testing, whereas stages MW and BK only vary in manufacturing method. It seems that the performance value failure temperature is linked to the composition of the asphalt mixture, but failure stress is rather based on manufacturing method.

4.2 Uniaxial Tension Stress Test

In figure 6 and 7 the results of the UTST (tensile strength and tensile strain) exemplary at a test temperature of -10 °C at the three stages of all investigated sections are sorted by asphalt and bitumen type.
The investigation with the UTST of the 21 sections pointed out, that a statistical difference between the three stages was only determined in eight sections at a test temperature of -25 °C. It is mostly stage EP which reaches in these cases the highest tensile strength. In the other 13 cases all three stages are statistically regarded as equal. In 14 cases stage BK reaches significantly lower tensile strength at a test temperature of -10 °C. 17 times stage MW reaches the highest tensile strength and besides in 14 cases a statistical difference to stage BK was found at a test temperature of 5 °C. In eleven cases there are statistical differences between all the three stages at a test temperature of 20 °C and also 18 times stage MW reaches the highest tensile strength.
At low temperature testing with the UTST (-25 and -10 °C) there are in general no statistically significant differences between the three stages by looking at the tensile strength and the tensile strain. At higher test temperatures of 5 and 20 °C there are increasingly statistical relevant differences between the stages, due to higher tensile strength at stages EP and MW.
The investigation with the UTST showed at all four test temperatures, that in laboratory produced specimens (stages EP and MW) reach generally higher tensile strength than specimens from drill cores (stage BK). These tendencies are not reflected by analyzing the failure strain. There is no consistent ranking between the three stages at each test temperatures of -25 and -10 °C. At a test temperature of 5 and 20 °C stage BK reaches mostly higher failure strains than stages EP and MW. But it was also shown, that only in four of 21 sections a statistical difference between failure strains of the three stages was found at a test temperature of -25 °C and only in two cases at a test temperature of -10 °C. In nine sections statistical differences between the failure strains were found at a test temperature of 5 °C and it is stage EP

and MW, which reach significantly lower failure strains. At a test temperature of 20 °C in 13 cases stage MW shows significantly lower failure strains than stage BK.
Here again no connection between conventional asphalt properties and performance features were found.

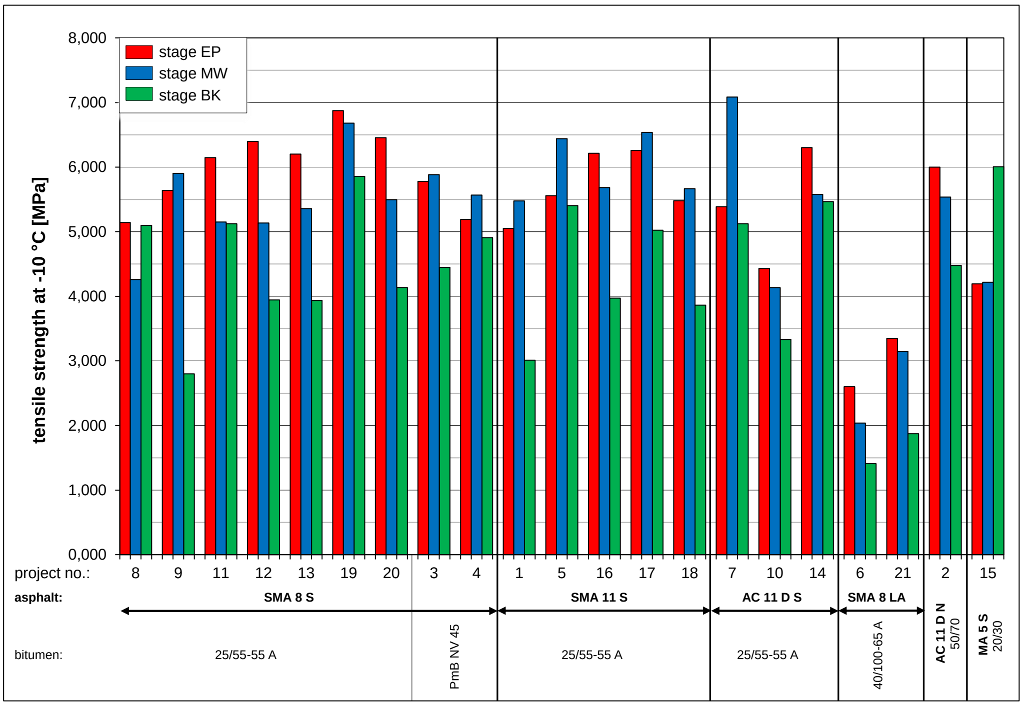


Figure 6: Tensile strength at -10 °C of the 21 sections at the three stages

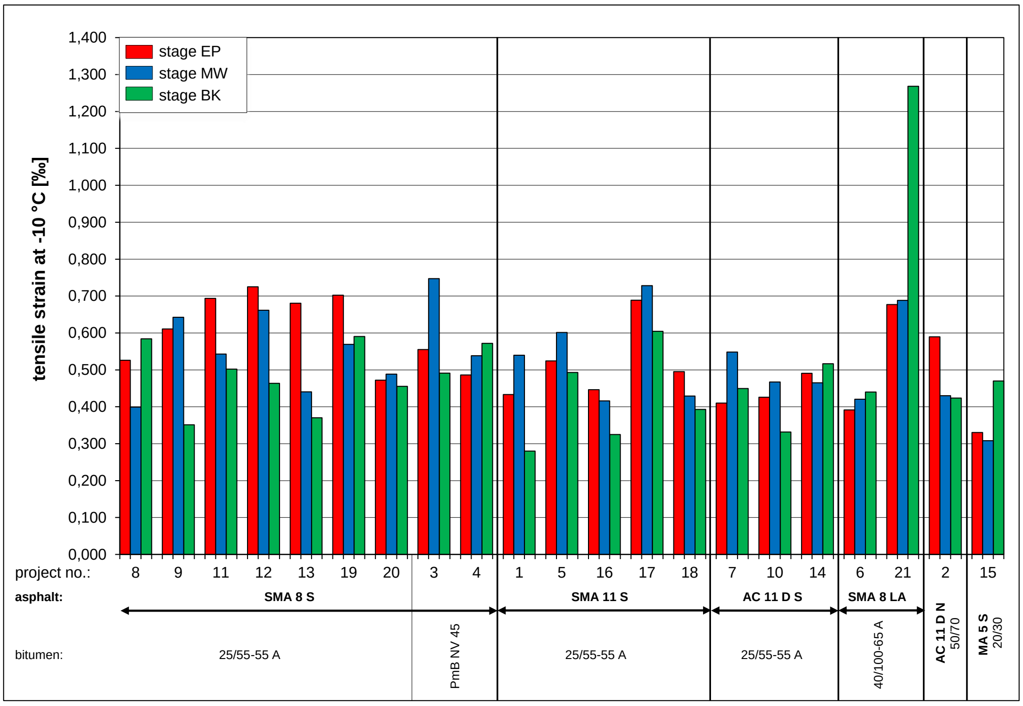


Figure 7: Tensile strain at -10 °C of the 21 sections at the three stages

4.3 Maximum Tensile Strength Reserve

Based on the results of the TSRST and the UTST on asphalt surfaces, the maximum tensile strength reserve and its associated temperature were calculated. The comparison of the maximum tensile strength reserve of the three stages shows a clearly higher level of the specimens, which are produced in the laboratory (stages EP and MW) in contrast to specimens from the paved asphalt layers (stage BK; figure 8). In 16 of 21 cases both stages – EP and MW – reach higher reserves than stage BK and just by comparing stage BK to stage MW, in 20 cases stage MW achieves higher reserves. Nevertheless there are great differences in the level of the maximum reserve by looking at the different asphalt types.

In most cases stage MW reaches higher temperatures according to the maximum tensile strength reserve in comparison to the stages EP and BK. 16 times stage EP reaches deeper temperatures than stage MW and 17 times it is stage BK, which reaches deeper temperatures. There were also great spans of the temperature detected between the three stages. The performance value temperature and maximum tensile strength reserve itself seem to stand in no connection to each other. This is for example shown in section no. 7, in which stage MW reaches a much higher reserve, but the associated temperature shows no conspicuities. Unlike section no. 10 that also reaches at stage MW a high reserve and furthermore an increased associated temperature. Even by considering the ranking of the two performance values, no similar series were found. However there are no relations between the maximum reserves and the associated temperatures.

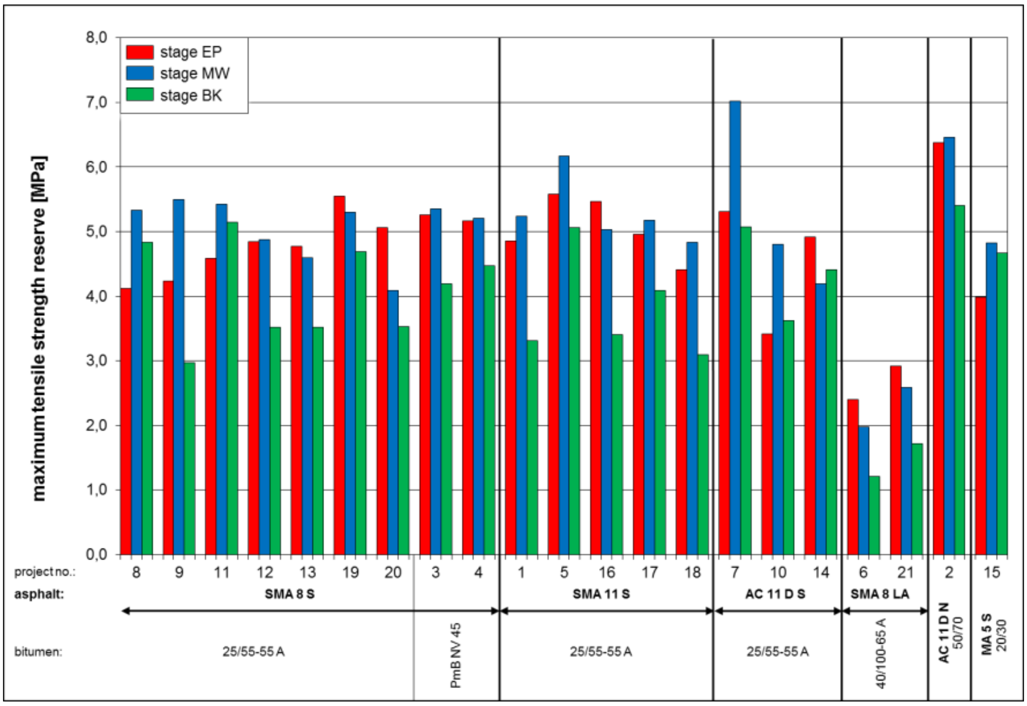


Figure 8: Maximum tensile strength reserve of the 21 sections

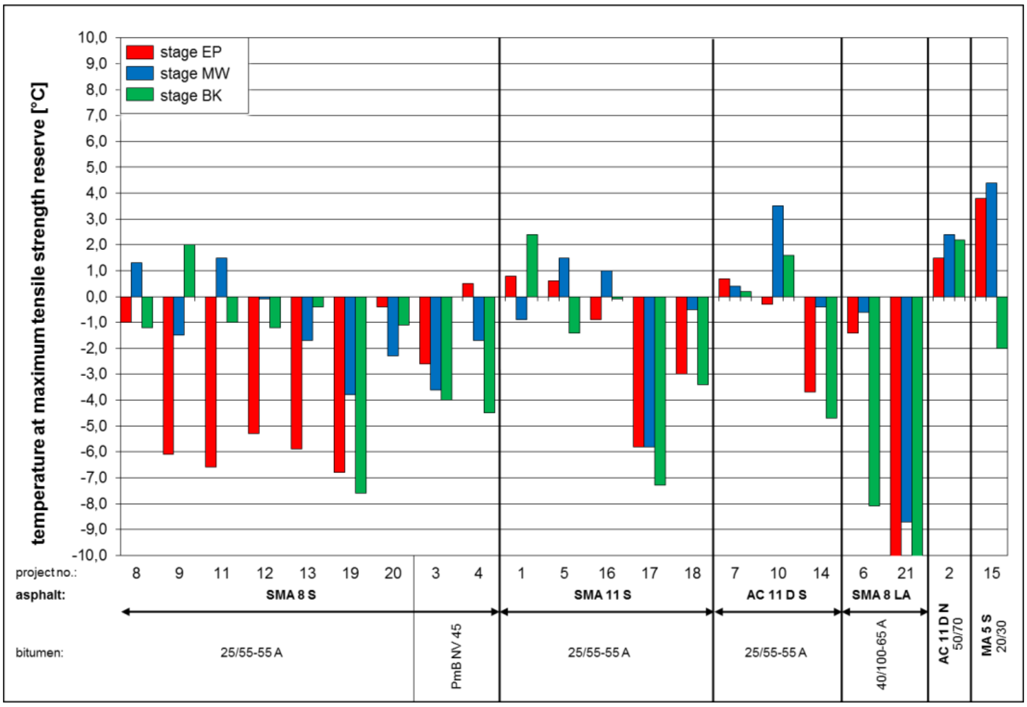


Figure 9: Temperature associated to the maximum tensile strength reserve of the 21 sections

5. CATEGORIZATION OF THE RESULTS

For low temperature behavior there are requirement categories defined in the EN 13108 (table 2), which are based on the performance value failure temperature gained from the TSRST. Based on the investigations the practicability of these categories is verified. The categorization requires a temperature of -15 °C as the lowest value of failure temperature in the TSRST. In 2,5 K intervals the categories extend to the highest category with a failure temperature of -30 °C. The three stages of the examined sections can be related to different quality grades in accordance with the mentioned categories (table 3). The sorting displayed that stage EP and MW are classified in the lowest category $TSRST_{max\ -15,0}$ for two times each, but only in one section this category is reached at both stages. The lowest category reached at stage BK is $TSRST_{max\ -17,5}$. The highest category $TSRST_{max\ -27,5}$ is reached at stages MW and BK. As another step the low temperature behavior of stages MW and BK was compared to the category of stage EP according to the EN 13108 (table 3). For stage MW of the asphalt surfaces in six cases a lower category than stage EP is reached and for stage BK only in three cases. In addition to this stage MW is in eight cases and stage BK in eleven cases classified in a higher category. In five cases even a category is skipped over in a higher or rather a lower category at each stage MW and BK. Only in seven of 21 cases the stages MW or BK are classified in the same category as stage EP.

Table 2: Categories for the maximum failure temperature $TSRST_{max}$ according to EN 13108-1

Maximum failure temperature °C	Category $TSRST_{max}$
-15,0	$TSRST_{max\ -15,0}$
-17,5	$TSRST_{max\ -17,5}$
-20,0	$TSRST_{max\ -20,0}$
-22,5	$TSRST_{max\ -22,5}$
-25,0	$TSRST_{max\ -25,0}$
-27,5	$TSRST_{max\ -27,5}$
-30,0	$TSRST_{max\ -30,0}$

Table 3: Classified low temperature resistance of the 21 investigated asphalt surfaces according to EN 13108-1

section	Low temperature resistance at stage EP	Low temperature resistance at stage MW		Low temperature resistance at stage BK	
1	$TSRST_{max\ -22,5}$	$TSRST_{max\ -22,5}$	√	$TSRST_{max\ -20,0}$	↓
2	$TSRST_{max\ -25,0}$	$TSRST_{max\ -22,5}$	↓	$TSRST_{max\ -25,0}$	√
3	$TSRST_{max\ -25,0}$	$TSRST_{max\ -25,0}$	√	$TSRST_{max\ -27,5}$	↑
4	$TSRST_{max\ -25,0}$	$TSRST_{max\ -25,0}$	√	$TSRST_{max\ -25,0}$	√
5	$TSRST_{max\ -22,5}$	$TSRST_{max\ -22,5}$	√	$TSRST_{max\ -22,5}$	√
6	$TSRST_{max\ -25,0}$	$TSRST_{max\ -25,0}$	√	$TSRST_{max\ -27,5}$	↑
7	$TSRST_{max\ -22,5}$	$TSRST_{max\ -25,0}$	↑	$TSRST_{max\ -27,5}$	↑
8	$TSRST_{max\ -22,5}$	$TSRST_{max\ -27,5}$	↑	$TSRST_{max\ -25,0}$	↑
9	$TSRST_{max\ -22,5}$	$TSRST_{max\ -25,0}$	↑	$TSRST_{max\ -22,5}$	√
10	$TSRST_{max\ -20,0}$	$TSRST_{max\ -22,5}$	↑	$TSRST_{max\ -22,5}$	↑
11	$TSRST_{max\ -20,0}$	$TSRST_{max\ 25,0}$	↑	$TSRST_{max\ -25,0}$	↑
12	$TSRST_{max\ -22,5}$	$TSRST_{max\ -27,5}$	↑	$TSRST_{max\ -25,0}$	↑
13	$TSRST_{max\ -22,5}$	$TSRST_{max\ -20,0}$	↓	$TSRST_{max\ -20,0}$	↓
14	$TSRST_{max\ -20,0}$	$TSRST_{max\ -17,5}$	↓	$TSRST_{max\ -22,5}$	↑
15	$TSRST_{max\ -15,0}$	$TSRST_{max\ -15,0}$	√	$TSRST_{max\ -20,0}$	↑
16	$TSRST_{max\ -17,5}$	$TSRST_{max\ -15,0}$	↓	$TSRST_{max\ -17,5}$	√
17	$TSRST_{max\ -20,0}$	$TSRST_{max\ -22,5}$	↑	$TSRST_{max\ -22,5}$	↑
18	$TSRST_{max\ -25,0}$	$TSRST_{max\ -20,0}$	↓	$TSRST_{max\ -20,0}$	↓
19	$TSRST_{max\ -22,5}$	$TSRST_{max\ -20,0}$	↓	$TSRST_{max\ -22,5}$	√
20	$TSRST_{max\ -15,0}$	$TSRST_{max\ -20,0}$	↑	$TSRST_{max\ -20,0}$	↑
21	$TSRST_{max\ -25,0}$	$TSRST_{max\ -25,0}$	√	$TSRST_{max\ -25,0}$	√

The determination of the performance-properties showed, that in general contractual requirements cannot be taken up easily according to the low temperature categories of EN 13108-1, due to the different and inconsequent classification of the three stages. Only in seven of 21 sections stage MW or stage BK were classified in the same category as stage EP, but this does not occur in the same sections. A clear specification of the dependencies between the three stages cannot be made at present with this method. However, it turned out that stage BK reaches in 18 cases at least the same or a higher category as stage EP. This is also in 15 times the case at stage MW.

6. SUMMARY

The investigation of low temperature behavior with the TSRST displays the influence of the manufacturing method of the specimens regarding the test results of failure stress. Specimens gained from cores from the paved asphalt layer show lower failure stress than specimens, produced in the laboratory by roller compactor. Asphalt mixture according to initial type testing mostly fractures earlier than tested samples from drill cores, which is shown in higher failure temperatures and in addition to this a higher stress is build up in these cases.
The investigations with the UTST showed no consistent ranking between the three stages and no statistical differences in performance properties of tensile strength due to manufacturing method or composition at low temperature testing (-25 and -10 °C). Just by looking at higher test temperatures of 5 and 20 °C more often significant differences were found between the three stages and it is mostly the mixture produced at a mixing plant, which reaches the highest tensile strength. At these test temperatures the samples gained from the paved layer mostly reach higher failure strains than roller compacted samples. But there is also no consistent ranking between the three stages at each test temperatures of -25 and -10 °C by looking at the failure strains. Whereas at a test temperature of 5 and 20 °C the drill core samples reach mostly higher failure strains than stages EP and MW.
Stage EP represents a composition according to the specifications of the initial type testing, whereas stage MW and BK only vary in manufacturing method. Therefore it was also examined, if conspicuities in conventional asphalt properties lead to outliers in the single performance features, but with these testing methods no relation was found in connection to the performance properties of low temperature behavior.
From the research it did appear that the maximum tensile strength reserve shows higher values at specimens compacted in the laboratory. In addition to this the mixture produced at a mixing plant reaches the maximum reserves at higher temperatures. A connection between the identified maximum tensile strength reserve and the associated temperature could not be found.
The attempt to use the categories according to EN 13108 to classify the three investigated stages, did not lead to consistent results. It turned out that the low temperature resistance can mostly be sorted in at least the same or a higher category as stage EP.

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