Resistance of Asphalt Binder and Surface Courses to High and Low Temperatures

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ABSTRACT: The two least desirable types of asphalt pavement distress consist of the permanent deformations, in the form of wheel-tracks, which are caused by heavy traffic loads at high temperatures, and of cracks which are caused by low temperatures. Asphalt mixes should be such that these two types of damage do not occur. In order to ensure the adequate resistance of asphalt mixes to high and low temperatures, their characteristics need to be verified in advance, before the road itself is constructed, i.e. during the design process in the asphalt laboratory. This can be done using the wheel–tracking test at high temperatures, which is a well-known test method, and is performed all over the world. In the European Union it has now been standardized in EN 12697-22. Determination of the resistance of asphalt mixes to low temperatures, i.e. to low-temperature cracking, can be performed by two different tests: the uniaxial tensile strength test, which is used to determine the resistance of asphalt mixes to tensile stress at low temperatures, and the thermal stress restrained specimen test (TSRST), which simulates the stress induced in such mixes by rapid temperature drops caused by changes in the weather.Since, in Slovenia, systematically assessed data are not yet available about the high- and low-temperature performance of asphalt binder and surface courses used on the national motorway network over the last ten years, this paper provides a description of the results of tests performed with the objective of creating such an assessment.

KEY WORDS: Low temperature, permanent deformation, thermal cracking, performance testing

1. INTRODUCTION

Tests of the resistance of asphalt mixes to permanent deformations at high temperatures have been carried out at IGMAT, the Building Materials Institute, Ljubljana, since 1997. During this time, by means of the Dry Wheel Tracking Test (DWTT), which is performed in accordance with BS 598-110:1998, the characteristics of all typical asphalts, particularly SMA (stone mastic asphalt), which are used on motorways and other roads with heavy traffic, have been investigated. However, during this period harmonized European standards came into force for the testing of asphalt mixes by assessing their resistance to wheel-tracking, i.e. SIST EN 12697-22:2004 (Small size device, procedure B). In 2006 IGMAT obtained the necessary equipment and staff to perform this kind of test, which was accredited by Slovenian Accreditation, and introduced on a regular basis. The question arises of how the results obtained by these two methods could be correlated, particularly in view of the lack of results of tests which have been performed according to the new method, which needs to be compensated.

So far low-temperature tests of asphalt mixes have not been performed at IGMAT. For this reason it was decided that these tests should be started, and that co-operation be established with ZAG Ljubljana, the Slovenian National Building and Civil Engineering Institute, which, in 2008, had obtained the necessary equipment for the performance of uniaxial tensile and cooling tests for the performance evaluation of asphalt mixes at low temperatures.

Apart from this, special equipment is needed for the preparation of test specimens of asphalt mixes for tests at high and low temperatures, so in 2008 IGMAT purchased a roller-compactor.

2. DESCRIPTION OF THE STUDY

When making a selection of different types of asphalt mixes for tests at high and low temperatures, particular attention was paid to the typical mixes for surface and binder courses, which are the most exposed to the effects of high and low temperatures due to their upper position in the pavement structure.

The following typical asphalt mixes for surface and binder courses were selected (each type of asphalt mix was represented by two variants; in some cases the mixes were prepared by different producers, whereas in other cases the mixes were prepared by the same producer but using different aggregates):

Table 1: Overview of the different types of investigated asphalt mixes

Asphalt mix reference number	Designation of asphalt mix according to SIST EN 13108-1 and SIST EN 13108-5
1	AC 11 surf 50/70
2	AC 11 surf PmB 45/80-65
3	SMA 8 PmB 45/80-65
4	SMA 8 PmB 45/80-65
5	SMA 11 PmB 45/80-65
6	SMA 11 PmB 45/80-65
7	AC 22 bin PmB 45/80-65
8	AC 22 bin PmB 45/80-65

Taking into account the binder in the above-listed mixes, it was decided to test the most frequently used combinations of these asphalt mixes and binders, i.e. paving-grade bitumen and polymer modified bitumen for the surface courses made from the asphalt mix AC 11 surf, and polymer modified bitumen for the binder courses made from the asphalt mixes SMA 8, SMA 11 and AC 22 bin.

Design of the above-listed asphalt mixes was performed according to the standard Marshall method, with the selection of optimum values of the proportions of bitumen, taking into account the expected traffic loads on different types of roads, where these mixes have already been used or will be used.

The selected asphalt mixes were sampled during their placing on individual sections of Slovenia's motorway network and state roads, where it was possible to later monitor the actual state of these asphalt mixes in the pavement structure, after it had been exposed to climatic and traffic loads.

At those locations where samples were taken of the asphalt mixes which were being placed there during the construction of individual sections of motorways and state roads, cores with a diameter of 200 mm were drilled from the placed asphalt layers. These cores were then subjected to tests in order to determine the resistance of these asphalt layers to high temperatures.

The results of the standard empirical tests, which were performed according to the testing standards of the series SIST EN 12697, are presented, for the investigated asphalt mixes and the corresponding recovered binders, in Tables 3 and 4.

If it is necessary to compare correctly the behaviour of test specimens of asphalt mixes in the laboratory with that of asphalt actually placed in a pavement structure, then the test specimens need to achieve approximately the same degree of compaction and the same thickness of layers as those corresponding to the as-placed asphalt, using the same type of compaction method as that used on-site. Taking into account the roller-compacting devices which are commonly used in countries such as Austria, Germany, the UK and the USA, it was decided to use the same kind of device.

The roller-compactor which was used to prepare the test specimens satisfies the requirements of the standard SIST EN 12697-33: 2004 "Bitumen mixes – Test methods for hot asphalt mixes – Part 33: Specimens prepared by roller compactor" and the German specification ALP A-StB - Part 11 [2].

The roller-compactor has a compaction mould with a filling attachment, and a roller segment, which has the shape of a cylindrical body. The asphalt mix, which is previously heated to the compacting temperature, is poured into the square-shaped compaction mould, and the asphalt is first pre-compacted. The next, main compaction is performed by applying the regulated force. During compaction, the mould, with dimensions of 305 x 305 x 40 (or 60) mm, moves on its trolley in one direction and the other, so that the roller segment acts on the upper surface of the asphalt slab in a kind of rocking movement.

The roller-compactor is computer-programmed in such a way that, after pre-compaction, the asphalt mix in the mould is further compacted up to the preset thickness, and then smoothed with a reduced force.

The test specimens of asphalt layers, prepared as described above in the shape of slabs, are used in the further testing at high and low temperatures. The slabs with dimensions of 305 x 305 x 40 mm are for asphalt mixes with granulations of up to 11 mm, and the slabs with dimensions 400 x 305 x 60 mm for asphalt mixes with granulations above 11 mm. After preparation, they are ready for further testing of the resistance of asphalt layers to the effect of permanent deformations at high temperatures, and for cutting into prismatically-shaped test specimens for determining the behaviour of asphalt layers at low temperatures.

3. RESULTS OF THE TESTS

The results of all of the standard empirical tests of hot asphalt mixes showed values which are in accordance with the requirements of the valid Slovenian Technical Specifications for Roads (known as "TSC"). They also showed that the mixes are suitable for use on roads with heavy and very heavy traffic loads.

In the majority of cases, the results of the measured characteristics of the placed asphalt layers made with the investigated asphalt mixes also satisfied the requirements of the TSC, except for the air voids content in the layers made of SMA 8 PmB 45/80-65 and SMA 11 PmB 45/80-65. This parameter has, in these two cases, values which are somewhat below the level of the requirement of the TSC (lower boundary: 3 % v/v).

The results of the tests of bitumens recovered from the asphalt layers after placing indicate hardening by one grade in comparison with paving-grade bitumen (input 50/70, recovered 30/45), whereas in the case of the polymer modified bitumen PmB 45/80-65 it was found that it had hardened to the recovered PmB 45/80-50 and PmB 25/55-65, and even to PmB 10/40-60, taking into account the penetration value and the softening point obtained by the ring-and-ball method. The results of the Fraass breaking-point, ductility and elastic recovery varied a great deal, so that it was not possible to define a rule with respect to the changes which occurred in comparison with the input bitumens.

3.1 Testing of asphalt mixes at high temperatures – resistance to permanent deformations

The results of tests of the resistance of asphalt layers to permanent deformations at high temperatures (see Figure 1 and Table 3), which were performed according to the standard SIST EN 12697-22 (Small size device, procedure B, at 60°C in air) on cores taken from placed layers and on slabs prepared in the laboratory by using the roller-compactor, can be evaluated as satisfactory, taking into account the repeatability of different tests of the same mix, which confirms the homogeneity and mutual comparability of the test specimens consisting of drilled cores of the same type of mix or layer. The absolute values of the obtained results corresponding to different types of asphalt show values which have the same order of magnitude, although there are some significant differences between them.

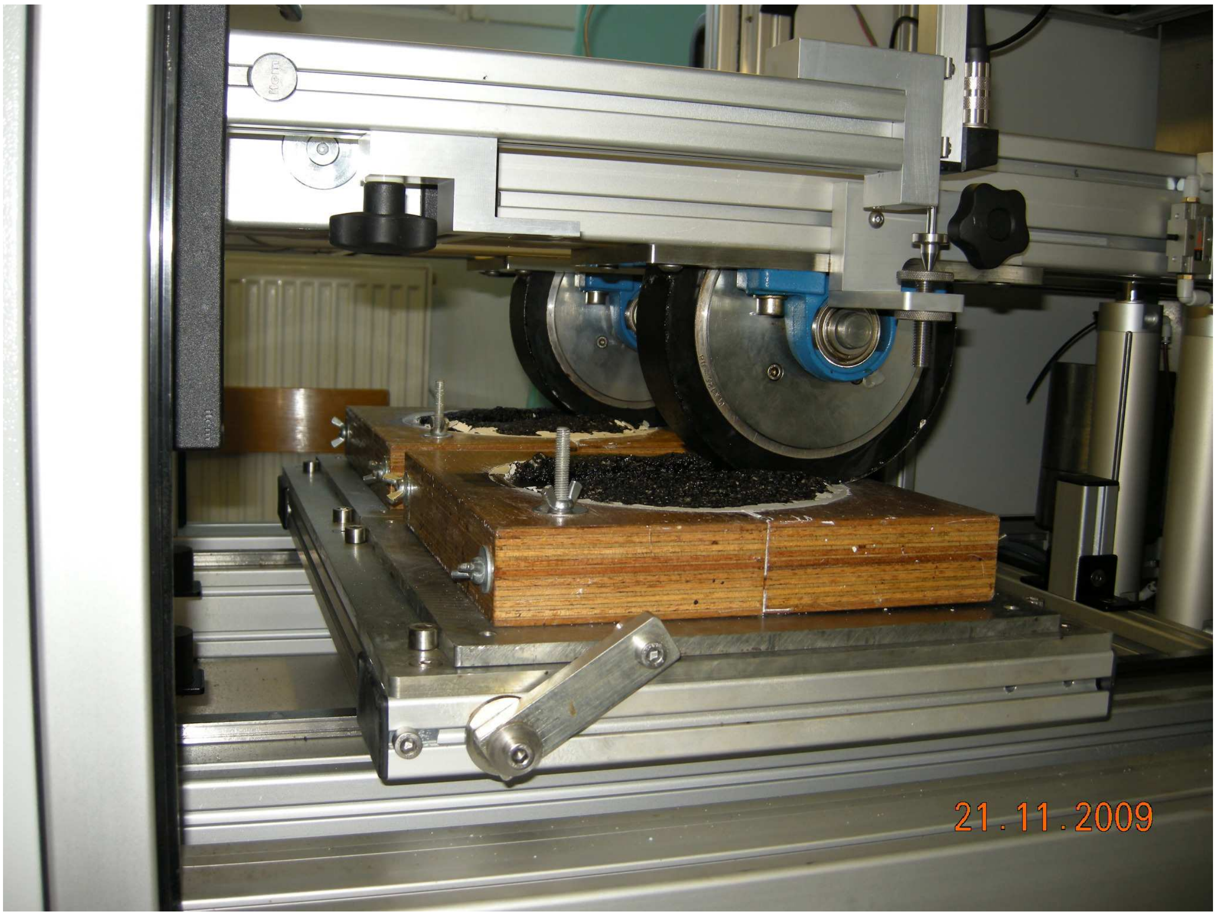

Figure 1: Wheel-Tracking Test apparatus according to the standard EN 12697-22 (small size device, procedure B, at 60°C in air) at IGMAT

In the case of the first two investigated asphalt mixes, AC 11 surf (with reference numbers 1 and 2), the results vary considerably, as was expected, taking into account the fact that paving-grade bitumen 50/70 was used first, and then the polymer modified bitumen PmB 45/80-65, which provided the expected better results. This shows that satisfactory resistance to wheel-tracking, which is prescribed in the standard SIST 1038-1 as being less than 7 % of the proportional rut depth for the heaviest traffic loads, can clearly only be achieved with the use of polymer modified bitumens.

The relatively large differences which can be seen in the results of the tests of resistance to permanent deformations at high temperatures also occur in the case of the two SMA 8 mixes (with reference numbers 3 and 4), not only in the case of the test specimens prepared with the roller-compactor in the laboratory in the form of slabs, but also in the case of the cores taken from layers of asphalt placed on site. These differences can be clearly ascribed to the considerable differences between the properties of both mixes and consequently the asphalt layers, since the properties of the recovered bitumens are, when compared, quite similar. The results are, in fact, situated somewhat above the values corresponding to the asphalt categories which are prescribed, at the present time, in SIST 1038-5, for roads with the heaviest traffic.

In the case of the SMA 11 asphalt mixes (with reference numbers 5 and 6), the differences in the results, between the two mixes, are the smallest. The results indicate the relatively good resistance of this type of asphalt mix to wheel-tracking, which is within the limits of the prescribed categories for SMA according to SIST 1038-5 (up to 5 % proportional rut depth for roads with the heaviest traffic).

The results of the tests carried out on the AC 22 bin asphalt mixes (with reference numbers 7 and 8) confirm the comparability of these two variants on the cores and slabs. The results show relatively high resistance to wheel-tracking among all the investigated types of asphalt mixes, which is, taking into account the maximum permitted proportional rut depth given in SIST 1038-1, which amounts to 3 %, to be expected, i.e. this confirms the correct relationship between the permissible values of the deformations and different proportional rut depths for the different types of asphalt mixes described in SIST 1038-1.

The results of tests, on cores, of the resistance of asphalt layers to permanent deformations at high temperatures, according to the procedure defined in SIST EN 12697-22, indicated the best values for the binder courses made of AC 22 bin PmB, which also satisfy the established requirement for the maximum proportional rut depth given in SIST 1038-1. They are followed by the SMA 11 type mixes, which also satisfy the corresponding requirement of SIST 1038-5, and then, fairly equally, by the AC 11 surf PmB and SMA 8 mixes, which do not entirely satisfy the corresponding requirements of SIST 1038-1 and -5.

3.2 Testing of asphalt mixtures at low temperatures

The properties of the investigated asphalt mixes at low temperatures, i.e. the resistance of asphalt to cracking at low temperatures, was investigated by means of two types of tests: uniaxial tensile tests and cooling tests.

Uniaxial tensile tests are performed at the following constant temperatures: T = + 20 °C, + 5 °C, - 10 °C and – 25 °C. Before the test starts the test specimen is stabilized without any load. After such stabilization for 2 hours at the selected temperature ±0,5°C, the test specimen is axially loaded at a constant strain rate of v = (1±0,1) mm/min. The results obtained from the uniaxial tension stress tests consist of the tensile strength and the failure strain corresponding to a particular test temperature. Failure must not occur in the adhesive. On the basis of the results of these tests, the relationship between tensile strength and temperature is defined by means of a third degree polynomial. At least three test specimens are tested at each test temperature.

The cooling test is used to simulate the loading of asphalt in the case of negative temperature changes due to cold weather. The test specimen is first conditioned for 2 hours in the thermostatic chamber (10±0,5)°C, and then, while maintaining constant length with fixed clamping, is continuously cooled. In order to perform the tests within a period of time which is acceptable in the laboratory, a cooling rate of T = - (10±0,5) K/h was selected. Due to the fact that temperature shrinkage is prevented due to the maintenance of constant length, forces occur in the specimen, which can be called cryogenic (i.e. they are caused by cooling) tensile stresses. Three test specimens are needed for each cooling test.

When the cryogenic stresses reach the region of the tensile strength, a crack occurs. The results of the cooling test include, apart from the relationship between the cryogenic stresses depending upon temperature, (1) the temperature at failure, which is the temperature when the crack occurs, and (2) the tensile stress at failure, which corresponds to the failure temperature. In order to be able to present the distribution of the cryogenic stresses and the calculations of tensile strength, the results of the cooling test are approximated by means of a third-degree polynomial.

The difference between the characteristic values of the tensile strength and those of the cryogenic stresses is designated as the tensile strength reserve. This tensile strength reserve determines a special characteristic of the asphalt, i.e that it is able to withstand, apart from the tensile stresses due to cooling, also the tensile stresses due to traffic loads. The ability of an asphalt to withstand cryogenic and mechanogenic tensile stresses is most pronounced where the tensile strength has its maximum value. The greatest tensile strength reserve Δßz and the temperature at which it occurs, are read off from the graph.

An example of results obtained in a cooling test is presented in Figure 2.

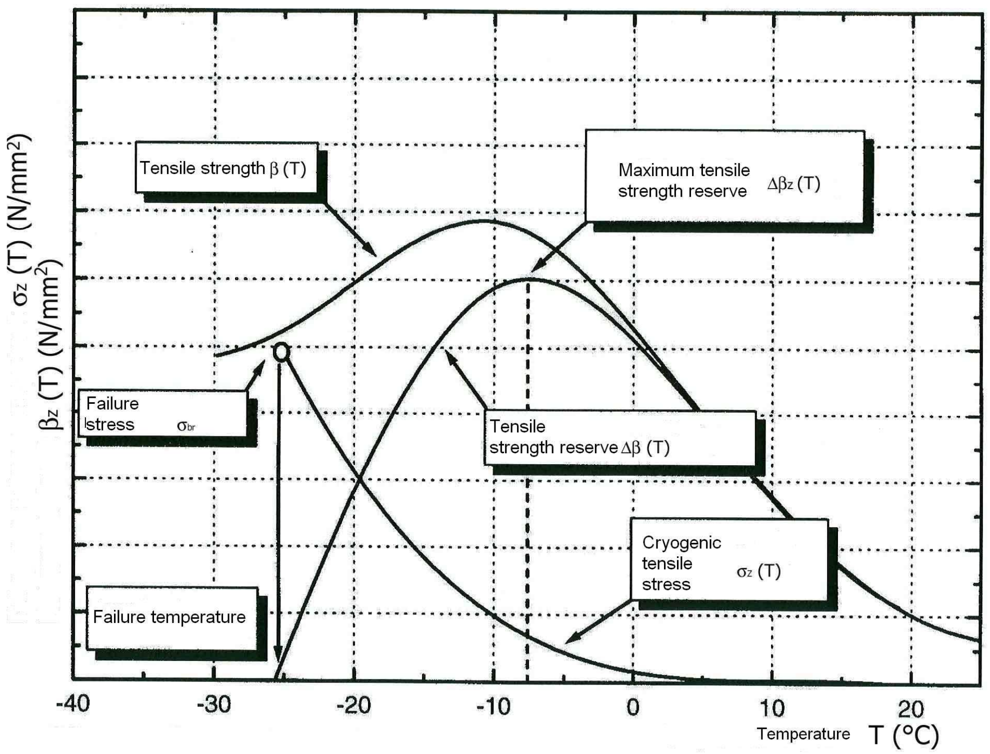

Figure 2: Typical distribution pattern of the cryogenic tensile stress σ_z (T), the tensile strength ß (T) and the tensile strength reserve $\Delta ß_z$ (T) in the temperature / stress diagram.

The apparatus for the performing of cooling tests at low temperatures (see Figure 3) consisted of a specially-converted universal testing machine, with a force-measuring system for forces up to ±50 kN, of Class 1 accuracy according to ISO 7500-1, and a system for measuring displacements consisting of LVDT sensors and a measuring range of ±5 mm with an accuracy of 0.5µm. A thermostatic chamber was used, which can provide working temperatures within the range between -40°C and 100°C, with a setting and measuring temperature accuracy of 0.1°C.

Figure 3: Apparatus for testing asphalt specimens at low temperatures in the thermo-static chamber at ZAG

Taking into account the results presented in Table 6, asphalt mix No. 4 (SMA 8 PmB 45/80-65) could be ascribed the most favourable behaviour at low temperatures, followed by asphalt mixes numbers 5, 3, 2, 7, 8, 6 and 1 (AC 11 surf 50/70).

In general, it was found that the differences between the results for the compared variants of the same asphalt mix types, i.e. SMA 8, SMA 11 and AC 22 bin, were small, except in the case of asphalt mix type AC 11 surf, where the difference between the test results obtained at low temperatures, for the two variants, was, due to the different types of bitumen used, considerable.

The results of the tests which were performed in order to determine the resistance of asphalt layers to cracking at low temperatures, in cooling tests and tensile loading tests at low temperatures on prismatically-shaped test specimens, made from test slabs, indicate (1) the best values for the asphalt mix type SMA 8 (the variant with a higher content of softer bitumen is better), (2) approximately equal results for both of the SMA 11 asphalt mixes and for one of the variants of the asphalt mix type AC 11 surf (the variant with polymer modified bitumen), followed by both of the binder courses (AC 22 bin PmB) and the second variant of the SMA 11 asphalt mix (with harder bitumen), whereas (3) the poorest results were, as expected, provided by the asphalt mix AC 11 surf with paving grade bitumen.

3.3 Comparison of the results of the high and low temperature tests

The comparative rankings of the investigated asphalt mixes with regard to their behaviour during high and low temperature tests are given in Table 2.

Table 2: Comparative rankings of the investigated asphalt mixes with regard to their behaviour during high and low temperature tests

Reference numbers and designations of the investigated asphalt mixes		Ranking of the investigated asphalt mixes with regard to their behaviour in high and low temperature tests							
		(1) **AC 11 surf**	**(2)** **AC 11 surf**	**(3)** **SMA 8**	**(4)** **SMA 8**	**(5)** **SMA 11**	**(6)** **SMA 11**	**(7)** **AC 22 bin**	**(8)** **AC 22 bin**
Results of the cooling tests	Failure stress (N/mm^2)	3.251 (8)	4.919 (2)	4.271 (5)	4.826 (3)	4.209 (6)	4.330 (4)	5.145 (1)	4.011 (7)
	Failure temp. (°C)	-21.4 (8)	-27.7 (3)	-27.3 (4)	-30.0 (2)	-31.5 (1)	-26.4 (5)	-24.3 (6)	-22.7 (7)
Maximum tensile strength reserve	Maximum (N/mm^2)	3.183 (8)	4.340 (5)	5.199 (2)	5.723 (1)	4.458 (4)	3.726 (7)	4.325 (6)	5.181 (3)
	at temp. (°C)	-1.6 (8)	-9.5 (5)	-11.7 (3)	-12.9 (2)	-13.5 (1)	-9.2 (6)	-6.9 (7)	-9.6 (4)
Results of the wheel-tracking test (on cores)	Rut depth (mm)	2.8 (8)	1.6 (5)	2.5 (7)	2.0 (6)	1.4 (3)	1.3 (2)	0.8 (1)	1.5 (4)
	Proportional rut depth (%)	7.9 (7)	4.2 (5)	9.3 (8)	6.6 (6)	3.3 (3)	3.3 (3)	1.3 (1)	2.4 (2)
	Wheel tracking rate (mm/1000p)	0.19 (8)	0.09 (7)	0.07 (4)	0.08 (6)	0.07 (4)	0.06 (2)	0.01 (1)	0.06 (2)
Overall ranking		**8th** (55)	**6th** (32)	**7th** (33)	**3rd** (26)	**1st** (22)	**4th=** (29)	**2nd** (23)	**4th=** (29)

Taking into account the results presented in Table 2, it can concluded that asphalt mix No. 5, i.e. SMA 11 PmB 45/80-65, shows the most satisfactory behaviour at high and low temperatures. This asphalt mix is followed by No. 7 (AC 22 bin PmB 45/80-65), No. 4 (SMA 8 PmB 45/80-65), numbers 6 and 8 (SMA 11 PmB 45/80-65 and AC 22 bin PmB 45/80-65), No. 2 (AC 11 surf PmB 45/80-65), No. 3 (SMA 8 PmB 45/80-65) and No. 1 (AC 11 surf 50/70).

4. CONCLUSIONS

The aim of the study, which was to use the results obtained by tests at high and low temperatures to characterize the asphalt mixes used in Slovenia's national motorway construction program, was largely achieved, since most of the used types of asphalt mixes were studied, whereas in the future it would be necessary to include asphalt mixes with newer types of polymer modified bitumens, which appeared later on the Slovenian market.

The asphalt mix which appeared to be the nearest to the optimum, i.e. the best compromise between resistance to permanent deformations and the best achievable behaviour at low temperatures, was, according to the results obtained, SMA 11 PmB 45/80-65 (number 5). This asphalt mix satisfied all the requirements with regard to resistance to permanent deformations, and at the same time achieved the lowest failure temperature during the cooling test and the lowest temperature at which the maximum tensile strength reserve occurred. This can be achieved only with a combination of (1) an asphalt mix composition, which, by itself, ensures high resistance to wheel-tracking, and (2) a high content of bitumen, which has as high as possible elasticity at low temperatures, but also sufficiently high viscosity (and a high softening point), which is in direct dependence with resistance to wheel-tracking.

A comparison of the results of the testing of the resistance of asphalt layers to cracking at low temperatures for the wearing course of type SMA 8 showed that the better mix is that with a higher content of bitumen, which itself has somewhat better properties at low temperatures, defined by the Fraass breaking-point and ductility. A comparison of these same two SMA 8 mixes also showed that, taking into account the similar properties of the bitumen, in the case of high temperatures the actual composition of the asphalt mix has an important effect on the resistance to permanent deformations, i.e. the granulation curve of the stone skeleton and, as a consequence, the mechanical-physical properties of the asphalt mix and layer, e.g. its air voids content.

The same is true of the tested AC 22 bin asphalt mixes for binder courses, which, designed and produced within the framework of the valid specifications with the use of PmB 45/80-65, provide satisfactory results particularly with regard to resistance to permanent deformations, whereas for the assessment of behaviour at low temperatures there are presently insufficient comparative results (they are, however, better than the present results obtained for the comparable asphalt mix type: AC 32 base 30/50).

Taking into account all of the above-described effects and inter-relationships, it appears to be possible to achieve a satisfactory compromise between the opposing properties of asphalt mixes at low and high temperatures, with careful selection of the input materials for these and their satisfactory design.

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Table 3:

RESULTS OF WHEEL TRACKING TESTS (EN 12697-22)

Nr.	Asphalt Mix Type	Level of Compaction	Void Content	Rut Depth	Proportional Rut Depth	Wheel Tracking Rate
		%	%V/V	mm	%	mm/1000p
1	AC 11 surf 50/70	100,5	5,0	2,8	7,9	0,19
2	AC 11 surf PmB 45/80-65	99,5	4,2	1,6	4,2	0,09
3	SMA 8 PmB 45/80-65	99,9	4,5	2,5	9,3	0,07
4	SMA 8 PmB 45/80-65	100,8	2,0	2,0	6,6	0,08
5	SMA 11 PmB 45/80-65	98,7	5,1	1,4	3,3	0,07
6	SMA 11 PmB 45/80-65	100,7	2,9	1,3	3,3	0,06
7	AC 22 bin PmB 45/80-65	101,1	4,9	0,8	1,3	0,01
8	AC 22 bin PmB 45/80-65	99,4	6,4	1,5	2,4	0,06

Table 4:

RESULTS OF LOW TEMPERATURE TESTING (prEN 12697-46)

Nr.	ASPHALT MIX TYPE	Binder content	ASPHALT MIX CHARACTERISTICS			COOLING TEST TSRST		UNIAXIAL TENSION TEST AT LOW TEMPERATURES				MAX. TENSILE STRENGTH RESERVE	
			Marshall specimens			ΔT = -10°C/h		@ 20°C	@ 5°C	@ -10°C	@ -25°C		
			Bulk Density	Max. Density	Air Voids	Failure Stress	Failure Temperature	Tensile Strength	Tensile Strength	Tensile Strength	Tensile Strength	Tensile Strength	at temperature
		m.-%	kg/m^3	kg/m^3	% (V/V)	MPa	°C	MPa	MPa	MPa	MPa	MPa	°C
1	AC 11 surf 50/70	5,1	2376	2516	5,6	3,251	-21,4	0,657	3,044	3,812	3,261	3,178	-1,6
2	AC 11 surf PmB 45/80-65	4,9	2511	2610	3,8	4,919	-27,7	0,568	2,595	5,162	4,557	4,340	-9,5
3	SMA 8 PmB 45/80-65	6,5	2466	2581	4,5	4,271	-27,3	0,635	2,559	5,981	5,303	5,199	-11,7
4	SMA 8 PmB 45/80-65	6,7	2393	2455	2,5	4,826	-30,0	0,506	2,169	6,221	5,489	5,723	-12,9
5	SMA 11 PmB 45/80-65	6,0	2401	2495	3,8	4,209	-31,5	0,433	1,650	4,764	4,732	4,458	-13,5
6	SMA 11 PmB 45/80-65	5,8	2511	2604	3,6	4,330	-26,4	0,550	2,344	4,691	3,997	3,726	-9,2
7	AC 22 bin PmB 45/80-65	3,8	2375	2525	5,9	5,145	-24,3	0,995	3,367	5,799	4,524	4,325	-6,9
8	AC 22 bin PmB 45/80-65	3,6	2506	2661	5,8	4,011	-22,7	0,810	3,248	6,578	5,704	5,181	-9,6