RECYPMA

Asphalt Mixtures Using Reclaimed Asphalt containing Polymer Modified Binder

Deliverable Nr.4.1

June 2013

The Netherlands Organization for Applied Scientific Research (TNO), the Netherlands

Delft University of Technology (DUT), the Netherlands

The University of Zilina (UNIZA), Slovakia

Danish Road Directorate, Danish Road Institute (DRI), Denmark

This project was initiated by ERA-NET ROAD.

Project Nr: 832699

Project acronym: RECYPMA

Project title:

Possibilities for high quality RECYling of Polymer Modified Asphalt

Deliverable Nr 4.1

Asphalt Mixtures Using Reclaimed Asphalt containing Polymer Modified Binder

Due date of deliverable: 30.6.2013

Actual submission date: 30.6.2013

Start date of project: 01.10.2011 End date of project: 30.09.2013

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Version: final report

This project was initiated by ERA-NET ROAD.

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Executive summary

Throughout Europe polymer modified asphalt (PMA) is used extensively in the past decades for high trafficked roads and premium pavements; especially for surface layers. The addition of polymers contributes to the durability and functionality of these premium pavements. These pavements are now more and more reaching their end of life. Therefore the road sector is facing a rapidly increasing source of reclaimed asphalt (RA) that contains polymer modified bitumen (PMB), which offers a potential premium binder contribution. It is the challenge to the road sector to ensure that the "RA containing PMB" will be recycled at its highest practical potential. The goal in recycling is not to achieve the highest possible recycling percentage, but to avoid downgrading of RA containing a potential valuable asset.

The aim of the RECYPMA project is to investigate the possibilities for recycling polymer modified asphalt from surface layers into new high quality surface layers using hot mix recycling. The project should give answers to the following questions:

- What is the potential of using PMRA in new asphalt?
- What is the benefit?
- What (do we think, regarding the results of the project) should be done to get this implemented (technically) based on laboratory test results?

The result of the project has been described in 4 reports:

1. Report on state of the art
2. Report on the properties of aged polymer modified binders
3. Report on asphalt mixtures using reclaimed asphalt containing polymer modified binder
4. Report on the benefits of asphalt using polymer modified RA

This report on asphalt mixtures using reclaimed asphalt containing polymer modified binder is the Deliverable 4.1 in the WP 4 of the project. It is focused on results of laboratory investigation that was performed in order to study the effect of the use of polymer modified reclaimed asphalt on the properties that describe the performance of asphalt.

Three different types of frequently used asphalt mixtures for wearing courses in European countries (SMA 11, AC 11 and PA 8) were investigated under laboratory conditions. Reclaimed asphalt (RA) containing bitumen with SBS modification was combined with virgin material in the tested mixtures. The RA percentages of 0, 15 and 40 respectively were used in these mixtures.

The following test were performed in order to assess the performance of the asphalt, in between the brackets is indicated what aspect of the performance of asphalt is asses by the test:

- water sensitivity test (*ITSR* values give information about durability with a respect to ingress of water);
- wheel tracking test (outputs of test provide an estimate of the resistance to rutting);
- stiffness and fatigue test (results can be used to estimate the structural life expectancy and will also give an impression on the integrity of the material).

The result of laboratory investigation is as follows:

- The ITSR values for all mixtures meet the requirements (the lowest value for SMA11 is 87, 1 %, for AC11 88, 2 % and 97,9 % for PA8). This means that the water sensitivity of the mixtures containing RA is expected to meet the requirements for surface layers.
- The ITSR values also show a relation between the tensile strength and the penetration of the blended binder as measured in WP3. This relation indicates that the binder in the mixtures is blended to such an extent that it dominates the behaviour of the mixture.
- ITSR values for PA mixtures are very high (all higher than 100 %). This might be caused by the basic nature of the filler.
- The wheel tracking test showed no rutting for all polymer modified binders. The mixtures with RA showed a similar performance compared to the reference mixture.
- The mixture with paving grade bitumen and without RA showed a significant amount of rutting. The mixture with the paving grade bitumen and 40% RA showed a better performance with respect to rutting. This might indicate an advantage of the remaining SBS in the binder. However it should be noted that this could also be the effect of the aged binder which has a higher softening point.
- The mixtures with RA with PMB have a higher stiffness compared to the mixtures without RA. This could be an advantage because a larger stiffness means a higher bearing capacity. However if the stiffness is very high, this could lead to brittleness at low temperatures. Therefore it is necessary to find a balance between needed stiffness and a risk of brittleness taking into account temperature conditions at a locality where a mixture is intended to be used. It can be verified by low temperature cracking and properties test according to EN 12697-46.
- The mixture with the paving grade bitumen and 40% RA showed better fatigue parameters compared to the mixture with paving grade bitumen and no RA. On the contrary the mixture with virgin PMB was the most fatigue resistant and an addition of RA decreased fatigue performance and fatigue life. It seems that the SBS content in blended bitumen is an important parameter. Remaining SBS in RAS binder increased fatigue resistance of the mixture with PGB. Due to SBS content in RAS binder, the SBS content in the blended bitumen for PMB mixtures with RA was lower then SBS content in the virgin PMB and therefore the RA mixtures showed an inferior fatigue performance.

Although the test results give information about selected properties of mixtures with reclaimed asphalt containing PMB they may not be representative for all polymer modified mixtures because only limited number of mixtures (especially with respect to fatigue) were tested in the frame of the project.

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List of abbreviations

AC	Asphalt concrete
DSR	Dynamic Shear Rheometer
DAC	Dense asphalt concrete
DUT	Delft University of Technology, The Netherlands
DRD	Danish Road Directorate, Denmark
EN	European norm
FTIR	The Fourier Transform Infrared spectroscopy
GPC	Gel Permeation Chromatography – molecular size distribution analysis
I_p	European abbreviation for penetration index, a calculated value based on Penetration in accordance with EN 1426 and softening point EN 1427.
ITS	Indirect tensile strength
ITSR	Indirect tensile strength ratio
PGB	Paving grade bitumen
Pen	Abbreviation for penetration at 25 ºC (EN 1426)
PMB	Polymer modified bitumen
PA	Porous asphalt
PRD_{air}	Proportional rut depth; parameter of asphalt rutting resistance derived from the test in a small size device model using the method B in air
RA	Reclaimed asphalt (US version: RAP - Reclaimed Asphalt Pavement)
RAD	Reclaimed asphalt from Denmark, SMA
RAN	Reclaimed asphalt from the Netherlands, PA,
RAS	Reclaimed asphalt from Slovakia, AC
RAD binder	Recovered binder from Danish reclaimed asphalt
RAN binder	Recovered binder from Dutch reclaimed asphalt
RAS binder	Recovered binder from Slovakian reclaimed asphalt
SMA	Stone mastic asphalt
SP	Softening point
TNO	The Netherlands Organisation for Applied Scientific Research
UNIZA	The University of Žilina, Slovakia
VFB	Voids filled with binder
V_m	Air void content
VMA	Voids in mineral aggregate
WTS_{air}	Wheel-tracking slope; parameter of asphalt rutting resistance derived from the test in a small size device model using the method B in air

1 Introduction and focus of the research

Throughout Europe polymer modified asphalt (PMA) is used extensively in the past decades for high trafficked roads and premium pavements; especially for surface layers. The addition of polymers contributes to the durability and functionality of these premium pavements. These pavements are now more and more reaching their end of life. Therefore the road sector is facing a rapidly increasing source of reclaimed asphalt (RA) that contains polymer modified bitumen (PMB), which offers a potential premium binder contribution. It is the challenge to the road sector to ensure that the "RA containing PMB" will be recycled at its highest practical potential. The goal in recycling is not to achieve the highest possible recycling percentage, but to avoid downgrading of RA containing a potential valuable asset.

The aim of the RECYPMA project is to investigate the possibilities for recycling polymer modified asphalt from surface layers into new high quality surface layers using hot mix recycling. The project should give answers to the following questions:

- What is the potential of using PMRA in new asphalt?
- What is the benefit?
- What (do we think, regarding the results of the project) should be done to get this implemented (technically) based on laboratory test results?

There are five Work Packages in the project plan as follows:

- WP1 – Management and knowledge dissemination
- WP2 – State of the art on recycling of modified binders
- WP3 – Properties of aged polymer modified binder
- WP4 – Properties of asphalt mixtures using reclaimed material with polymer modified binders
- WP5 – Environmental and economic benefits of the use of polymer modified reclaimed asphalt

The main objectives of WP4 were:

- to investigate the influence of the combined binder on the chosen properties of the asphalt according to the relevant test methods defined in European Standards;
- an analysis of the test results and
- evaluation of the properties of mixtures with RA and compare them to the performance of reference mixtures.

The main aim of laboratory tests was investigation what effect has the use of polymer modified reclaimed asphalt on the properties of asphalt that describe the performance of an asphalt mixture.

Three different types of frequently used asphalt mixtures for wearing courses in European countries (SMA 11, AC 11 and PA 8) were investigated under laboratory conditions. Reclaimed asphalt (RA) containing bitumen with SBS modification was combined with virgin material in the tested mixtures. The RA percentages of 0, 15 and 40 respectively were used in these mixtures. Detailed description of used materials, the combinations of virgin materials and RA, the procedure of mixtures production and the test samples preparation can be found in the Chapter 2.

The testing program and the test procedures are described in the Chapter 3. The following properties describing performance of asphalt were tested:

- water sensitivity test (*ITSR* values give information about durability with a respect to ingress of water);
- wheel tracking test (outputs of test provide an estimate of the resistance to rutting);
- stiffness and fatigue test (results can be used to estimate the structural life expectancy and will also give an impression on the integrity of the material).

The results of the individual tests are presented and discussed in the Chapter 4 and the general conclusions are presented in the Chapter 5.

Moreover, DRD has made a lot of microscopy images of thin and plane sections of asphalts used in the RECYPMA project and prepared the separate report on microscopy analysis (Nielsen & all 2013) that shall be seen as an annex to the Deliverable 4.1.

2 Materials, design and production of mixtures, preparation of test samples

2.1 Materials and mixtures

The three different types of asphalts for wearing courses were selected (SMA, AC and PA), designed and produced for laboratory testing. The aim was to study performance of asphalts with different content of reclaimed asphalt (RA). Binder in RA was SBS polymer modified bitumen. Five combinations of virgin binder and RA were used for each type of asphalt. One virgin paving grade bitumen (PGB) and one virgin polymer modified bitumen were used in combination with three contents of RA (0 %, 15 % and 40 % respectively). The review of mixtures to be tested is in Table 2.1. As can be seen the mixtures with PGB + 15 % RA were not produced and tested. The reason is that irrespectively of the polymer level in the reclaimed asphalt it would only have “diluted” the polymer to a level where no effect of the polymer can be expected. In this very low concentration the polymer cannot create the required network to affect the material behaviour.

Table 2.1 Matrix of tested mixtures

RA content of	SMA 11		PA 8		AC 11	
	PGB	PMB	PGB	PMB	PGB	PMB
0 %	x	x	x	x	x	x
15 %	–	x	–	x	–	x
40 %	x	x	x	x	x	x

2.2 Virgin binders

Four virgin binders were used to produce the mixtures with RA. Two paving grade bitumen and also two SBS polymer modified bitumen. Distribution into the tested mixtures was as follows:

Binders to produce the AC 11 and PA 8 mixtures:

Q8,	straight run bitumen, paving grade 70/100, offered by Kuwait Petroleum (Nederland) B.V.
KR,	modified bitumen by mixing 10% of D0243 SBS in B160/220 bitumen, produced by Kraton Polymers Nederland BV.

Binders to produce the SMA 11 mixtures:

70/100,	straight run bitumen in accordance with EN 12591. It was produced by blending two different bitumens which were used in a Danish Round Robin on bituminous binders in the winter of 2005/2006. The 70/100 was blended from the two round robin samples 7212-584 (40/60) and 7212-583 (330/430) in the proportion 71.2 % and 28.8 % respectively.
90/150-75,	SBS polymer modified bitumen in accordance with EN 14023. It was provided by Colas Danmark A/S as a reference sample from their production of polymer modified bitumens.

The standard and fundamental properties of these virgin binders (penetration, softening point, viscosity, chemical characterisation) are presented in the Deliverable 3.1.

2.3 Aggregate and fillers

Aggregate and fillers commonly used for the SMA11 production in Denmark, the AC11 production in Slovakia and the PA8 production in Netherlands were used in the scope of the project. Following aggregate and fillers were used into the individual mixtures:

SMA 11	Aggregate	8/11,2 mm 5,6/8 mm 2/5,6 mm 0/2 mm	Durasplit, natural aggregate from Norway
	Filler	Limestone filler Hydrated lime	to provide stiffening of the bituminous mortar and improving the adhesion between the aggregate and the binder
	Fibres		Cellulose fibres

PA 8	Aggregate	8/11,2 mm 5,6/8 mm 4/5,6 mm 2/4 mm	FjordStone, natural aggregate from the Netherlands
	Sand	< 2 mm	Crushed Sand
	Filler	Wigro 60K	Limestone filler with 25 - 35 % hydrated lime
	Fibres		Cellulose fibres

AC 11	Aggregate	8/11,2 mm 4/8 mm 2/4 mm	Kamenec, andesite natural aggregate from Slovakia
		0/2 mm	Limestone, natural aggregate from Slovakia
	Filler	Limestone	extra fine milled

2.4 Reclaimed asphalts

Three reclaimed asphalts, RAN, RAS and RAD, were obtained by milling from surface layer (PA, AC11 and SMA11) and crushing. Detailed information about these different RA is given below.

RAN,	7 year old reclaimed from the top layer of a double porous asphalt system with. It was located at one section between Den Bosch and Eindhoven on Expressway A2 in the Netherlands. The brand is Styrelf PMB 40/100-65 HD.

RAS,	reclaimed from dense asphalt concrete (AC11) produced by Cesty Nitra in 1996 and paved on a section of motorway in the vicinity of town Sereď. The name of binder at time of production was called Apollobit MCA-S. It was SBS polymer modified bituminous binder with a penetration range between 50 -100 x 0,1 mm and a softening point above 70 ºC.
RAD,	reclaimed from Stone Mastic Asphalt (SMA 11) produced by Colas Danmark A/S in 1989 and paved on a motorway in Denmark (Jutland, north of the town of Vejle). The bituminous binder at the time of production was called Caribit Plus 85 which was a SBS polymer modified bituminous binder with a penetration ranging from 70 – 100 x 0,1 mm and a softening point Ring & Ball above 75 °C.

During milling of the old surface layer the gradation of the aggregate has changed a little bit as the milling operation has created a little higher amount of fines. Particle size distributions of RAD and RAS are shown in Figure 2.1 and Figure 2.2 respectively. The RAS and RAD were used as one fraction and RAN was distributed into two fractions (> 5,6 mm and < 5,6 mm). The mixture design reflects on gradation of aggregate mixture from RA.

The binder content in reclaimed asphalts was determined by extraction procedure according to EN 12697-1. Dichlormethane was used as a solvent in compliance with conclusions of the Deliverable 2.1. The obtained binder contents in RA are given below:

RAN,	5,42 %
RAS,	5,05 %
RAD,	4,60 %

2.5 Design of mixtures

An application of a high percentage of RA materials with SBS polymer modified bitumen in a mixture has to be tested in the RECYPMA project. The RA content of 0 %, 15 % and 40 % was specified to meet the RECYPMA project objectives.

The mixtures SMA 11, AC 11 and PA 8, each of them with the mentioned RA content, were designed according to requirements and practices commonly used in Denmark (for SMA11), Slovakia (for AC11) and Netherland (for PA8). It was fundamental to have more or less the same particle size distribution (the same aggregate gradation) for RA contents of 15 % and 40 % as for “the benchmark mixture” with RA content of 0 %. Dosage of virgin binder for mixtures with RA content of 15 % and 40 % was calculated taking into account RA content in a mixture and content of bitumen in RA. The final recipes are given in Tables 2.2 - 2.4 and Figures from 2.1 to 2.3.

Table 2.2 Mixture design: Percentage of various components in the five mixtures of SMA 11

Mixture groups	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5
Nominal RAD %	0 % RAD	40 % RAD	0 % RAD	15 % RAD	40 % RAD
Virgin binder type	70/100 SV 12135 Straight run paving grade bitumen		90/150-75 SV 12129 Polymer modified bitumen		
Virgin binder	6,09	3,73	6,09	5,20	3,73
Filler – limestone	2,11	1,92	2,11	1,89	1,92
Filler – hydrated lime	2,10	1,92	2,10	1,89	1,92
Durasplit 0/2 mm	16,38	5,75	16,38	13,22	5,75
Durasplit 2/5 mm	5,62	0,00	5,62	0,00	0,00
Durasplit 5/8 mm	11,23	4,79	11,23	11,33	4,79
Durasplit 8/11 mm	56,17	43,14	56,17	51,95	43,14
RA (binder + aggregate)	0,00	38,45	0,00	14,22	38,45
Fibres	0,30	0,30	0,30	0,30	0,30
SMA 11 mixture	100,00	100,00	100,00	100,00	100,00

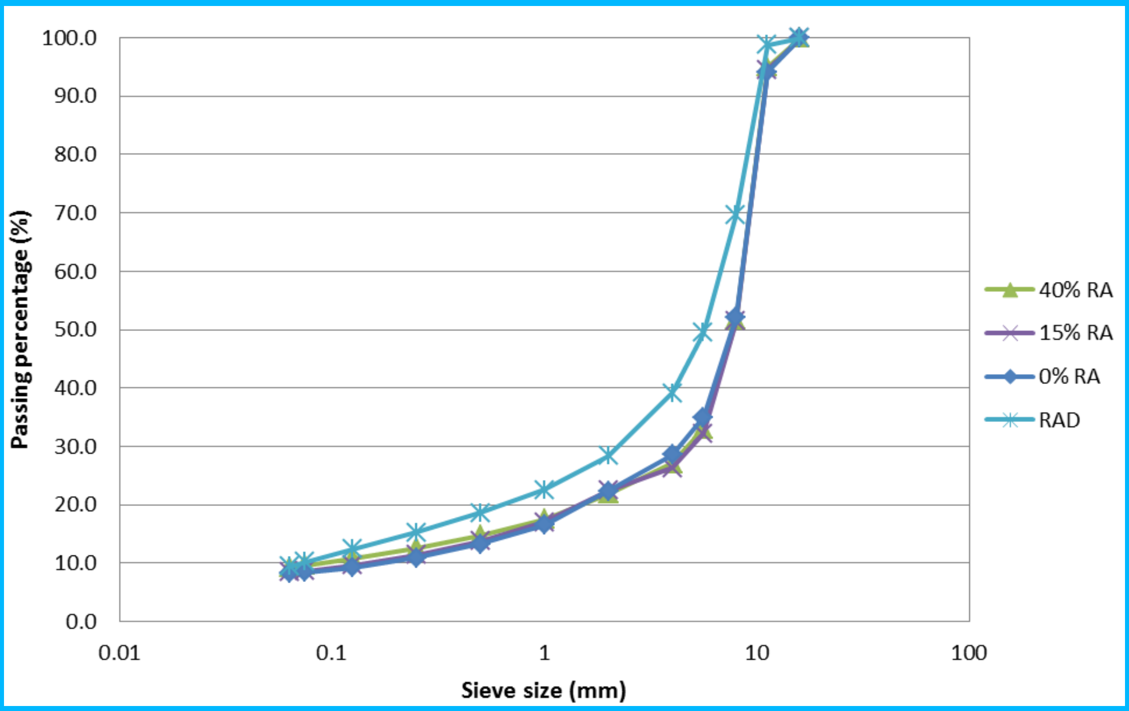


Figure 2.1 Aggregate gradation of old RAD and new SMA 11 mixtures with different content of RAD

Table 2.3 Mixture design: Percentage of various components in the five mixtures of AC 11

Mixture groups	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5
Nominal RAS %	0 % RAS	40 % RAS	0 % RAS	15 % RAS	40 % RAS
Virgin binder type	Q8 (70/100) Paving grade bitumen		Kraton (PmB 70/100-83) Polymer modified bitumen		
Virgin binder	5,60	3,69	5,60	4,88	3,69
Filler	7,08	5,66	7,08	6,61	5,66
0/2 mm	29,26	12,27	29,26	22,66	12,27
2/4 mm	15,58	9,44	15,58	13,22	9,44
4/8 mm	22,66	17,94	22,66	20,77	17,94
8/11 mm	19,82	11,33	19,82	16,99	11,33
RA (binder + aggregate)	0,00	39,67	0,00	14,87	39,67
AC 11 mixture	100,00	100,00	100,00	100,00	100,00

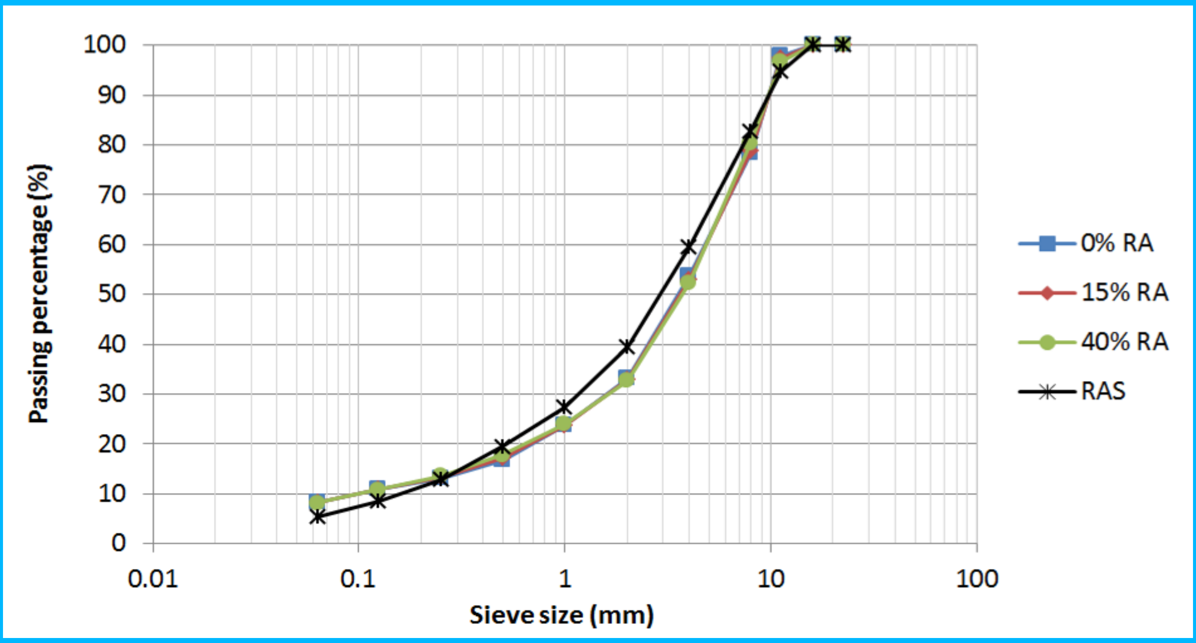


Figure 2.2 Aggregate gradation of old RAS and new AC 11 mixtures with different content of RAS

Table 2.4 Mixture design: Percentage of various components in the five mixtures of PA 8

Mixture groups	Mixture 1	Mixture 2	Mixture 3	Mixture 4	Mixture 5
RA %(Aggregate)	0%	40%	0%	15%	40%
RA% (Aggregate+binder)	0%	41.74%	0.00%	15.66%	41.74%
Fjordstone 4/8 (one fraction)	86.57%	57.42%	86.57%	75.64%	57.42%
Virgin binder type	Q8 (70/100) Paving grade bitumen		Kraton (PmB 70/100-83) Polymer modified bitumen		
Virgin binder	5.48	3.74	5.48	4.82	3.74
Wigro 60K - filler	4.71	1.26	4.71	3.42	1.26
Sand Brekerzand (+ Steen < 2 mm)	7.86	1.10	7.86	5.32	1.10
FjordStone C 11,2 – C 8 mm	2.08	1.38	2.08	1.81	1.38
FjordStone C 8 – C 5,6 mm	47.79	31.70	47.79	41.76	31.70
FjordStone C 5,6 – C 4 mm	24.51	16.26	24.51	21.43	16.26
FjordStone C 4 – 2 mm	7.48	4.96	7.48	6.53	4.96
RA (binder + aggregate) Granulaat Microdek > C 5.6	0.00	26.34	0.00	9.88	26.34
RA (binder + aggregate) Granulaat Microdek < C 5.7	0.00	13.17	0.00	4.94	13.17
Afdruipremmer Fibres	0.09	0.09	0.09	0.09	0.09
PA 8 mixture	100.00	100.00	100.00	100.00	100.00

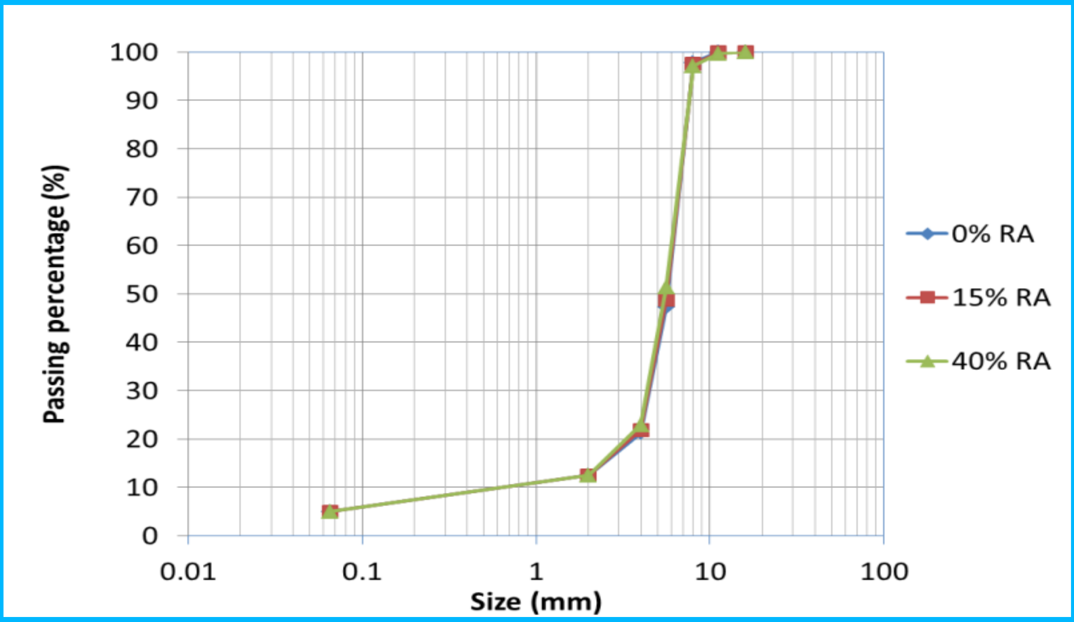


Figure 2.3 Aggregate gradation of new PA8 mixtures with different content of RAN

2.6 Production of mixtures

The most common purpose for laboratory mixing is to obtain the optimal properties of the asphalt material to be mixed. Therefore it was necessary to pay attention to the whole process related to production of mix (steps, order, mixing time and temperatures) to achieve a homogenous mixture with optimum properties. The following premises and requirements were stated in the conclusions of the Deliverable 2.1 as for mixing of asphalts with RA in a laboratory:

- preparations of materials
    - the reclaimed asphalt material has to be granulated to the desired size of agglomerates and dried;
    - the aggregates are dried;
    - if a virgin binder is supplied in large buckets the binder must be melted, homogenised and poured into suitable container sizes prior to mixing the asphalt;
    - fibres must be completely dry and to be taken apart in rather small lumps;
- heating and mixing temperatures of materials
    - a mixing temperature has to be specified/stated according to the rheology of virgin binder, reclaimed binder and supplier reference (in case of modified bitumen);
    - a reclaimed asphalt has to be heated at temperature below or equal to the mixing temperature;
    - virgin aggregates has to be heated to the mixing temperature;
    - a virgin bituminous binder in sufficient amount has to be heated to the mixing temperature;
    - fibres have to be dried at (110 ± 5) °C;
- time of heating and mixing
    - a reclaimed asphalt has to be heated for a short period of time (no more than two hours), time depends on the amount of RA material in final mixture;
    - time of virgin aggregates heating depends on theirs amount, whole amount has to be heated to a specified temperature;
    - a virgin bitumen has to be heated for shortest time applicable for the purpose;
    - fibres have to be heated approx. two hours prior to mixing.

All requirements/recommendation above were respected when the mixtures were produced in the laboratory according to EN 12697-35+A1. Because the production process with superheating of virgin aggregate (in order to compensate lower temperature of RA during a mix production) was not accepted in the RECYPMA project, all materials (virgin aggregates, filler, reclaimed asphalt and virgin bitumen) were heated to mixing temperatures according to Table 2.4 before mixing. The mixtures were produced in the laboratory shaft mixer equipped with thermostatically controlled heating and mechanical speed control. The following mixing steps and times were applied to achieve a homogeneous SMA11 and PA8 mixture:

- virgin aggregates and fibres (fibres heated on the temperature of 110 ^{0}C) were poured in the laboratory mixer (see Figure 2.4) and mixed for 30 s (see Figure 2.5);
- reclaimed asphalt was added (see Figure 2.6) and mixed for 30 s (see Figure 2.7);
- virgin binder was added (see Figure 2.8) and mixed for 90 s (see Figure 2.9);
- filler was added (see Figure 2.10) and mixed for 60 s (see Figure 2.11).

The same procedure was applied for AC11 production; only fibres were excluded in this case.

Table 2.5 Mixing and compacting temperatures

Mixture	Virgin binder	Temperature in ^{0}C	
		heating and mixing	specimen preparation
SMA 11			
MIX1, 0% RAD	PGB 70/100	155	145
MIX2, 40% RAD		165	155
MIX3, 0% RAD MIX4, 15% RAD MIX5, 40% RAD	PMB 90/150-75	180	170
AC 11			
MIX1, 0% RAS	PGB Q8 (70/100)	155	145
MIX2, 40% RAS		165	155
MIX3, 0% RAS MIX4, 15% RAS MIX5, 40% RAS	PMB Kraton (70/100-83)	170	160
PA 8			
MIX1, 0% RAN	PGB Q8 (70/100)	155	145
MIX2, 40% RAN		165	155
MIX3, 0% RAN MIX4, 15% RAN MIX5, 40% RAN	PMB Kraton (70/100-83)	170	160

Figure 2.4 Aggregates and fibres in laboratory mixer

Figure 2.5 Aggregates and fibres after mixing

Figure 2.6 Addition of reclaimed asphalt

Figure 2.7 Aggregates, fibres and reclaimed asphalt after mixing

Figure 2.8 Addition of virgin bitumen

Figure 2.9 Mixture with virgin bitumen

Figure 2.10 Addition of filler

Figure 2.11 Final mixture

2.7 Preparation of test samples

The produced mixture was adjusted to the compaction temperature according to Table 2.5. Two devices for compaction of the mix were used. The impact compactor according to the EN 12697-30 was used for production of cylindrical test samples with the diameter of 101,6 ± 0,1 mm and the height of 63,5 ± 2,5 mm (for determination air voids content, water sensitivity and stiffness). The roller compactor according to the EN 12697-33+A1 with controlled compaction energy was used to produce slabs for wheel tracking and 2PB fatigue test (the samples for 2PB fatigue test were cut from the slabs).

3 Testing program and procedures

3.1 General

The main aim of laboratory tests was investigation of the effect of the use of polymer modified reclaimed asphalt on the properties of asphalt. The following test were performed in order to assess the performance of the asphalt, in between the brackets is indicated what aspect of the performance of asphalt is asses by the test:

- water sensitivity test (*ITSR* values give information about durability with a respect to ingress of water);
- wheel tracking test (outputs of test provide an estimate of the resistance to rutting);
- stiffness and fatigue test (results can be used to estimate the structural life expectancy and will also give an impression on the integrity of the material).

All mentioned tests were carried out according to the relevant European standards.

3.2 Detailed testing program

Three types of asphalt commonly used for wearing course were tested. Although two of them were dense graded mixtures and one was open graded, all mixtures (without and with RA content) were exposed to water sensitivity, wheel tacking and stiffness test. Fatigue test was applied only on AC mixes (see Table 3.1), as there are no requirements for fatigue in Denmark on SMA and in the Netherlands on PA.

Table 3.1 Matrix of performed tests

Test	Mixture		
	PA8	SMA11	AC11
Air voids content	x	x	x
Water sensitivity (*ITSR*)	x	x	x
Wheel tracking test	x	x	x
Stiffness	x	x	x
2PB fatigue test	–	–	x

3.2.1 Air void content

The air voids content V_m was determined according to EN 12697-8. It was calculated using the maximum density of the mixture (determined according to EN 12697-5, volumetric procedure A with water) and the bulk density of the compacted asphalt (determined according to EN 12697-6). The method for determination of the bulk density was chosen with respect to the guidance of EN 12697-6, Annex A. The procedure B – saturated surface dry (SSD) was applied for the AC 11 and SMA 11 mixtures and the procedure D – by dimensions was used for PA8 mixtures.

Basic information about the test is as follows:

The bulk density of compacted specimen:

- 4 test specimens;
- Sample compaction – impact compactor, 2 x 50 blows;
- SMA 11 and AC 11 mixtures – the procedure B – SSD dry;
- PA8 mixtures – the procedure D – by dimensions.

The maximum density of mixture:

- 2 test specimens;
- procedure A – volumetric procedure with water

3.2.2 Water sensitivity

The water sensitivity of bituminous specimens (*ITSR*) was tested according to EN 12697-12 method A on the base of indirect tensile strength of dry and wet cylindrical specimens.

Six specimens were prepared in the laboratory for each combination of virgin materials and RA using 2 x 35 blows of the impact compactor. The prepared specimens had diameter of 101,6 ± 0,1 mm and height of 63,5 ± 2,5 mm.

The test specimens were divided into two subsets (according to bulk density and height) and conditioned before testing. The dry subset was stored at laboratory temperature of 20 ± 5 ^{0}C. The wet subset after saturation in the vacuum container was stored in a water bath at 40 ± 1 ^{0}C for a period of 68 to 72 hours.

After conditioning the indirect tensile strength test of each specimen was determined in accordance with EN 12697-23 at test temperature of 25 ± 2 ^{0}C. The indirect tensile strength ratio was calculated using average indirect tensile strength of the wet and dry subset.

3.2.3 Resistance to permanent deformation

The characteristics of resistance to permanent deformation (WTS_{AIR} and PRD_{AIR}) were determined in accordance with EN 12697-22+A1 (Wheel tracking test). A test device, conditions and number of cycles were selected according to EN 13108-20, Annex D as follows:

- a small size device;
- procedure B;
- conditioning and testing – in air at the test temperature of 50 ± 1 ^{0}C;
- 10 000 load cycles;
- 2 test specimens for each test.

Two test samples (slabs with dimensions of 260 mm x 300 mm and thickness of 40 mm) were prepared in the laboratory for each combination of virgin materials and RA using compactor in accordance with EN 12697-33+A1.

The rut depth was continuously recorded and a relationship between the rut depth and number of load cycles was plotted during the testing. After testing a wheel tracking slope WTS_{AIR} was calculated from the rut depth curve (the values at 5 000 and 10 000 load cycles were used) and a proportional rut depth PRD_{AIR} at 10 000 cycles was determined.

3.2.4 Stiffness

Stiffness of the tested mixtures was determined according to EN 12697-26, method C (the test applying indirect tension to cylindrical specimens (IT-CY)).

Six specimens were prepared in the laboratory for each combination of virgin materials and RA using 2 x 50 blows of the impact compactor. The prepared specimens had diameter of 101,6 ± 0,1 mm and height of 63,5 ± 2,5 mm. Exact dimensions (diameter and height) and bulk density were determined for each of specimens before testing.

Stiffness of each specimen was determined at four temperatures (0 °C, + 10 °C, + 15 °C, + 20 °C and + 30 °C). After conditioning to the test temperature the test procedure was performed in the universal servo-hydraulic testing machine as follows:

- Placement of the test specimen to LVDT alignment jig;
- Settings of LVDT sensors;
- Entering the input data needed for measurement (high, diameter, Poisson, horizontal diametral deformation);
- Application of 10 conditioning pulses;
- Application of 5 load pulses – the variation of applied load and horizontal diametral deformation with time were measured and recorded and load area factor was determined;
- Rotation of the specimen through 90° and repeating of measurements (10 conditioning pulses and 5 load pulses).

The outputs of measurements from 5 load pulses were used to calculate stiffness modulus of the specimen according to the equations and guidelines in the EN 12697-26, method C. The stiffness modulus of a mixture was calculated as the mean of values determined for individual specimens.

3.2.5 Resistance to fatigue

The fatigue tests were performed only on the mixtures of AC 11 (A1 – A5). As it was mentioned in the Chapter 3.2, the reason is there are no requirements for fatigue in Denmark on SMA and on PA in the Netherlands. The two-point bending test on trapezoidal shaped specimens with controlled displacement according to EN 12697-24 was applied.

The specimens for the test were sawed from slabs made in laboratory according to EN 12967-33. The dimensions of specimens fulfilled the criteria determined in EN 12697-24, Annex A, Table A.1 for mixes with maximum nominal size of aggregate D ≤ 14 mm.

The tests were performed at the temperature of + 10 °C and the frequency of 25 Hz. Eighteen specimens were tested for each mixture. Each specimen was moved sinusoidally at its head to impose the required displacement until the failure criterion has been reached (crack occurring or force decreasing to 50 % of the initial value). The various displacements were used to have values approximately regularly spaced on a logarithmic scale and also to have results for number of cycles to failure criterion N ≤ 10^6 and N ≥ 10^6 (according to EN 12697-24 it should be at least one third of results for the each group).

Using the test results, the fatigue line was determined in a bi-logarithmic system as a linear regression of fatigue life versus amplitude levels. The strain ε_6 corresponding to an average of 10^6 cycles and the slope of the fatigue line 1/b were determined. Then, following parameters were calculated:

- the estimation of the residual standard deviation S_N

$$S_N = S_{lg(N)} \times \sqrt{\frac{(1-r_2^2)\times(n-1)}{n-2}}$$

- the quality index $\Delta\varepsilon_6$

$$\Delta\varepsilon_6 = 0{,}5\varepsilon_6 \times (10^{-2b\times S_0} - 10^{2b\times S_0})$$

where:

$$S_0 = S_N \times \sqrt{\left[\frac{1}{n} + \frac{(lg(\varepsilon_6) - lg(\varepsilon))^2}{(n-1)\times S^2_{lg(\varepsilon)}}\right]}$$

4 Results and discussion

The chapter presents results of tests carried out on three types of asphalt: asphalt concrete (AC), stone mastic asphalt (SMA) and porous asphalt (PA). Various combinations of virgin aggregate, reclaimed asphalt and binders were used for each type of asphalt. Influence of variability in composition of asphalt on basic volumetric characteristics, water sensitivity, resistance to rutting, stiffness and fatigue is presented below. A discussion regarding the test results is also included.

4.1 Basic volumetric characteristics

The volumetric characteristics of compacted asphalt as

- air void content – V_{m},
- voids in a mineral aggregate – *VMA* and
- voids filled with a binder – *VFB*

provide some indications of its expected performance in pavements. Values of all these characteristics are influenced by

- bulk density of test specimens - ρ_b,
- maximum density of loose mixture - ρ_m,
- binder content in a specimen – *B* and
- density of binder - ρ_B.

Volumetric characteristics of mixtures, calculated according to EN 12697-6 and EN 12697-8, are presented in Figures 4.1 – 4.9.

Maximum density of loose mixture

Regarding maximum density of loose mixture, a basic assumption is that maximum density of loose mixtures with the same material and particle size distribution should be the same. It is possible to state validity of the assumption for SMA mixtures although there is a difference in binders (and probably in their densities). It can be seen in Figure 4.1 that values for two percentages of RAD (0 % and 40 %) and the binders 70/100 and 90/150-75 are approximately the same. A similar situation can be observed for AC, where the differences in the values for RAS content of 0 % and 40 % are small and the different densities of the binders can be an explanation (see Figure 4.4). A different situation can be observed in the case of PA. The difference between maximum densities for RAN content of 40 % is relatively small but there is higher value for RAN content of 0 % in Figure 4.7. Probably repeatability of the test has higher influence in the case of the RAN content of 0 % compared to the previous situations.

Moreover, differences in the values of maximum densities for the different RA content can be observed in Figures 4.1, 4.4 and 4.7. It can be explained by a difference in bulk densities between aggregate in RA and virgin aggregate (for example bulk density of aggregate in RAD is 3,018 g.cm^{-3} and bulk density of virgin aggregate is 2,785 g.cm^{-3}). Maybe slight differences in aggregate gradation can also play a role. There are various ratios between fine and coarse particles in mixture of aggregate. Generally, higher content of fines particles can lead to higher values for the maximum density because fine particles can fill the voids in between the large particles which increases the bulk density.

Bulk density of compacted mixture

Various factors influence numeric values of bulk density of the compacted mixture. Bulk density of aggregate, shape of aggregate particles and workability of mixture that relates to compaction temperature and viscosity of binder are the most important ones.

Influence of bulk densities of virgin aggregate and RA is evident in Figures 4.1, 4.4 and 4.7. Increasing RA content in SMA and AC mixtures (for both binders) leads to the higher values of bulk densities. The reason is that the densities of RAD and RAS are higher compared to the densities of virgin aggregate. The densities of PA behave in the opposite direction, because of higher density of the virgin aggregate.
When the mixtures with the same RA content but a different binder are compared, higher values of bulk densities for paving grade bitumen (PGB) in comparison with polymer modified bitumen (PMB) can be observed. This is probably due to a lower workability of the mixtures with PMB. This lower workability is in spite of higher mixing temperatures. The compaction temperature of 160 ^{o}C recommended by the producer of PMB was not high enough from the viscosity of binder point of view.

Air void content

Air void content V_m relates to ratio of bulk and maximum density. Due to the reasons described in the previous paragraphs focused on bulk and maximum density the air void content is decreasing in the case of SMA and AC and increasing for PA (see Figures 4.2, 4.5 and 4.8).

Voids in mineral aggregate and voids filled with bitumen

Air void content V_m, bulk density, binder content and binder density are inputs for *VMA* calculation. Because the binder content is the same for all tested mixtures, the difference in density between PGB a PMB is not significant and the bulk density for the individual binder contents do not differ greatly, *VMA* values depend mainly on V_m. For this reason *VMA* values decrease (SMA and AC) or increase (PA) when the RA content changes from 0 % to 40 % (see Figures 4.3, 4.6 and 4.9).

As product of the bulk density, binder content and binder density do not differ greatly for the individual RA contents, *VFB* depend mainly on *VMA* values. *VMA* is in inverse relation to *VFB*, it means, higher *VMA* is a cause of lower *VFB* and vice versa. The values in Figures 4.3, 4.6 and 4.9 are in accordance with it.

Conclusions

Taking into account the basic volumetric characteristics of all tested mixtures it is possible to state that design of mixtures with relatively high content of RA (up to 40 %) can be done. Results have shown it is possible to combine virgin aggregate, virgin binder and reclaimed asphalt in such way that all requirements related to air voids content, voids in mineral aggregate or voids filled with binder are fulfilled.

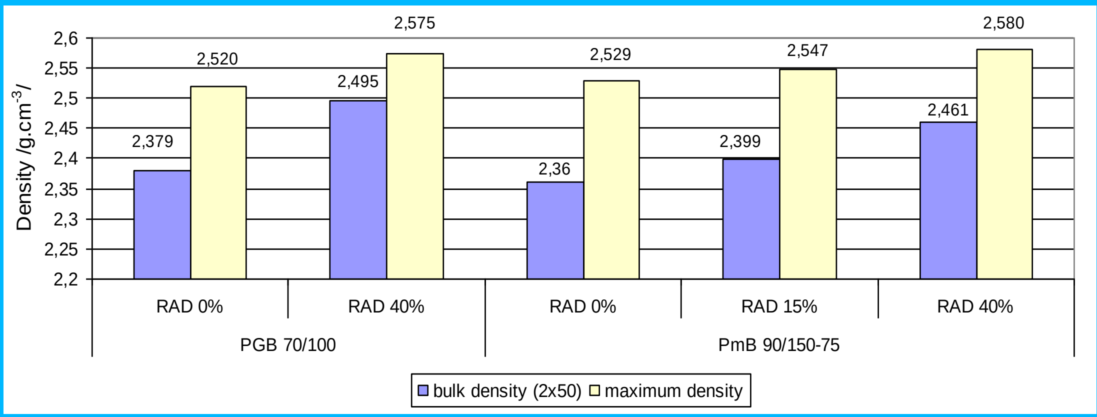


Figure 4.1 Bulk and maximum densities of SMA mixtures with different content of RAD

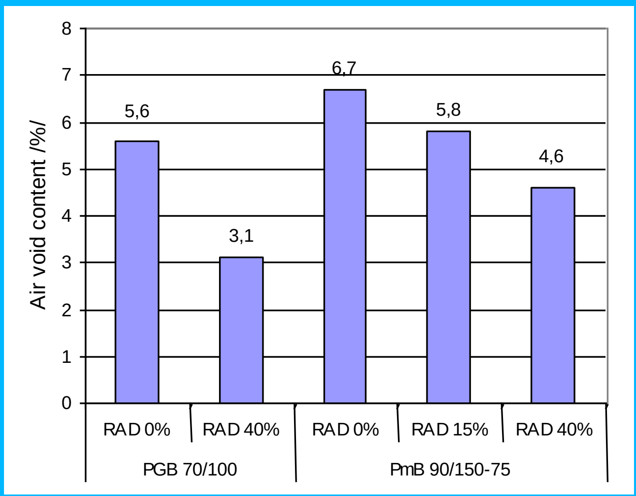


Figure 4.2 Air void content of SMA mixtures with different content of RAD

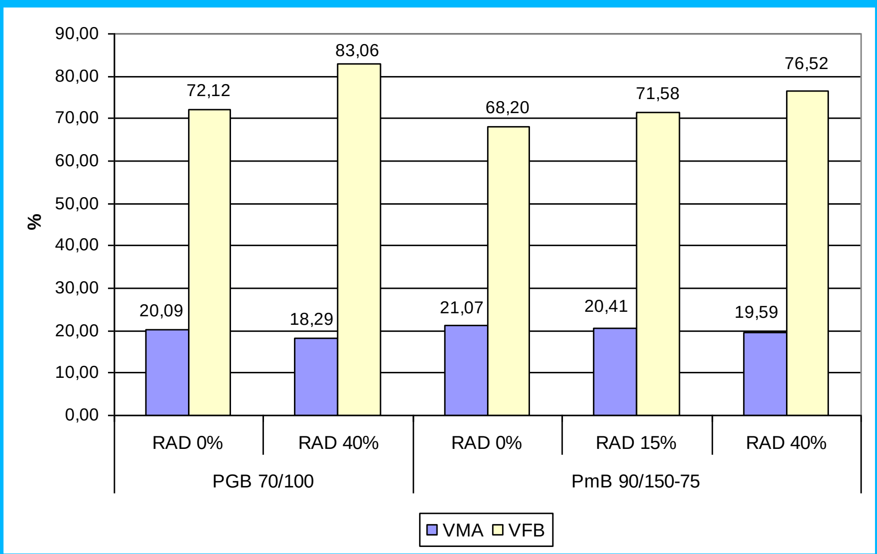


Figure 4.3 *WMA* and *VFB* of SMA mixtures with different content of RAD

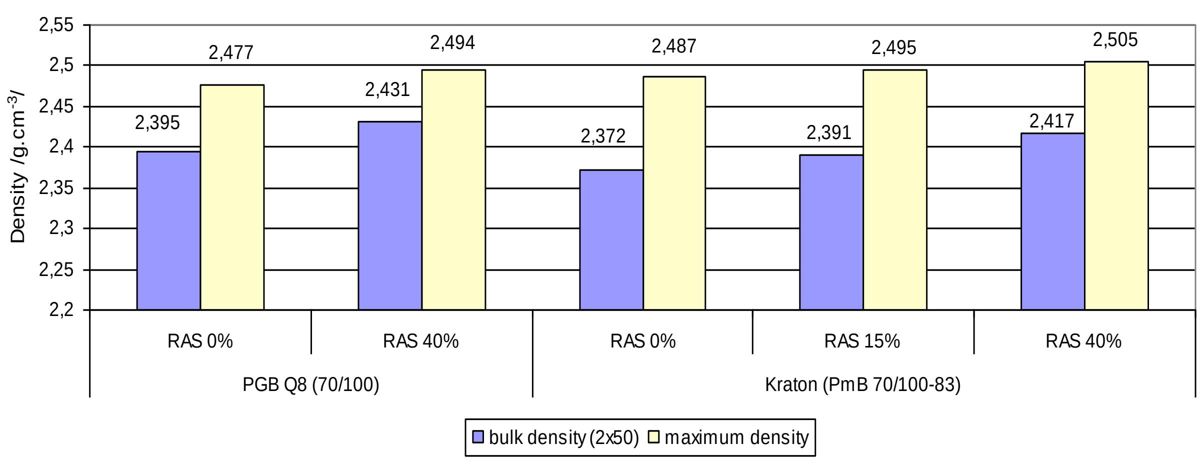


Figure 4.4 Bulk and maximum densities of AC mixtures with different content of RAS

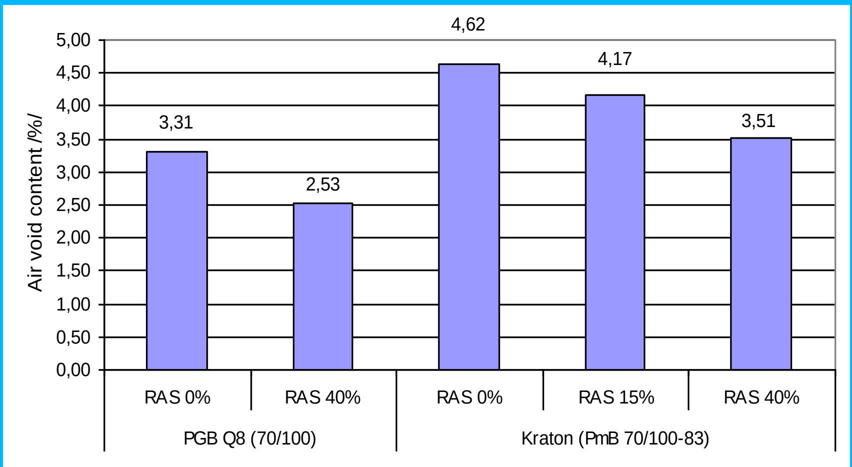


Figure 4.5 Air void content of AC mixtures with different content of RAS

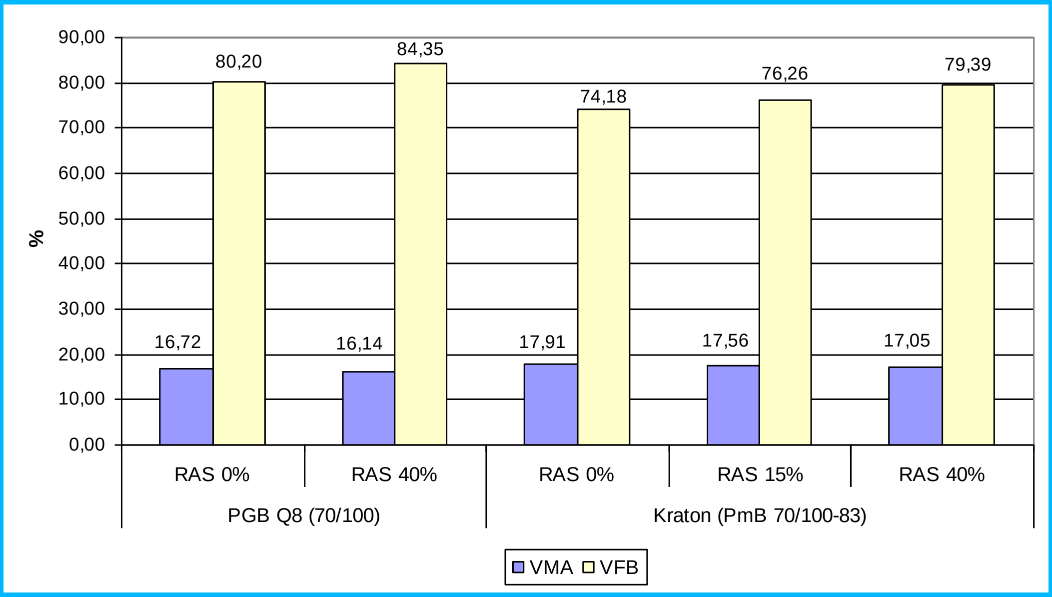


Figure 4.6 *WMA* and *VFB* of AC mixtures with different content of RAS

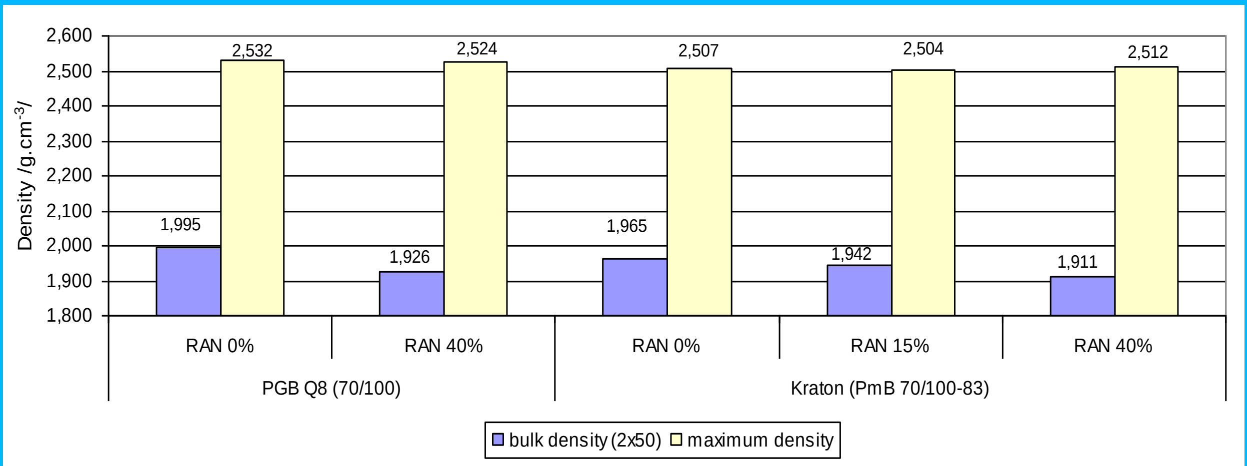


Figure 4.7 Bulk and maximum densities of PA mixtures with different content of RAN

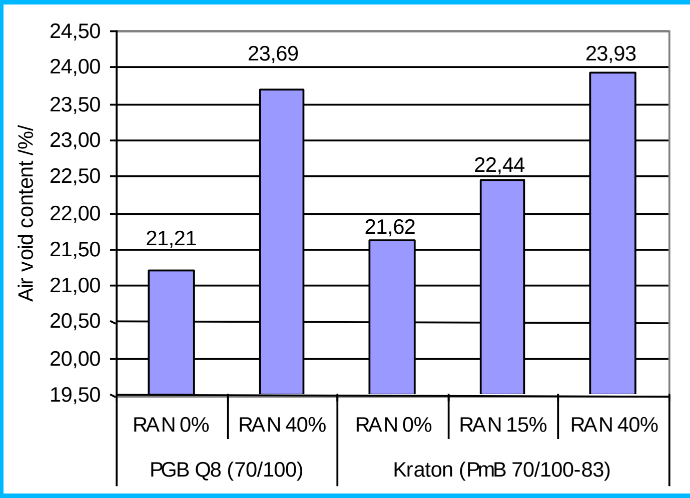


Figure 4.8 Air void content of PA mixtures with different content of RAN

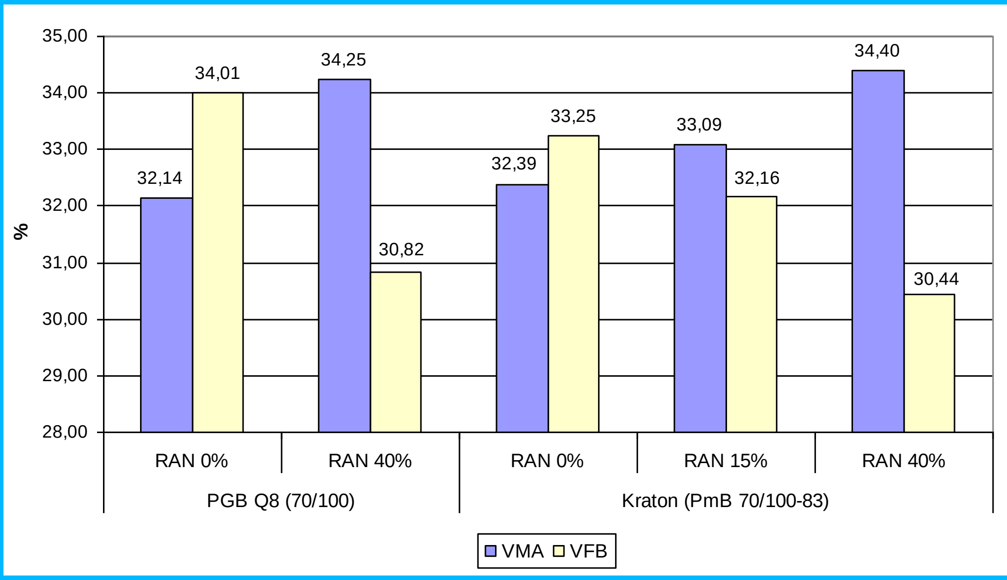


Figure 4.9 *WMA* and *VFB* of PA mixtures with different content of RAN

4.2 Water sensitivity

Strength of dry and wet samples and water sensitivity of all mixtures is shown in next Figures (from 4.10 to 4.21).

It is evident in the case of SMA there are higher values of *ITS* (both, dry and wet) for higher RAD content in Figure 4.10. It can be considered as a positive influence of RA addition but it is necessary to take into account that strength is obviously linked to air voids content in the case of dense graded asphalts. Specimens with lower air voids content should have higher values of *ITS*. The values in Figure 4.12 confirm this relation. The relationship between air voids content and strength can be used as one of explanations why the *ITS* values of dry and wet samples with the same content of RAD are higher for paving grade bitumen. Second explanation relates to the penetration of blended binder (the virgin PMB and RAD binder) and the test temperature for the *ITSR* test (25 ^{o}C). As can be seen in Figure 4.13, penetration of blended binders with the PGB 70/100 is lower than penetration of blended binders with the PMB 90/150-75 for the same content of RA. It could also lead to higher values of strength when PGB was used.

The values of *ITSR* are slightly different, comparing the mixtures with PGB and PMB (see Figure 4.11). These are almost the same as for the mixtures with PMB regardless the different content of RA. But the *ITSR* values of mixtures with PMB decrease with increasing RAD content. It seems the blended binder with higher portion of RAD binder has worse affinity to the virgin aggregate. But it is necessary to be aware these differences can be caused by numerous tiny variations in sample compaction, aggregate gradation, binder content etc. Besides that, the numeric values of *ITSR* are very high, the value for 0 % of RAD is higher than 100 % (i.e. *ITS* of wet samples was higher then *ITS* of dry samples). In addition to that, the precision of the *ITSR* test, which is 15 % for repeatability, should be also taken into account.

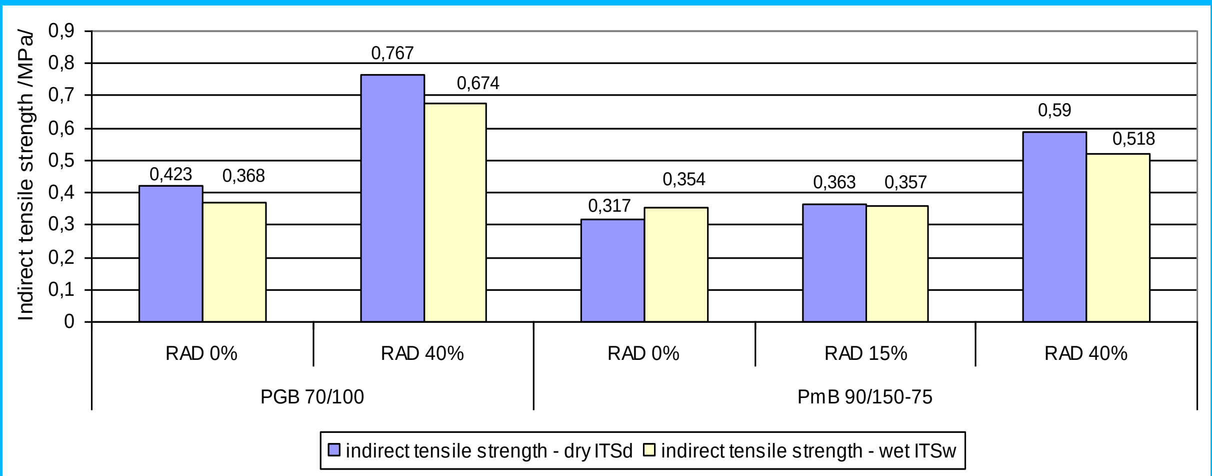


Figure 4.10 *ITS* of SMA mixtures with different content of RAD

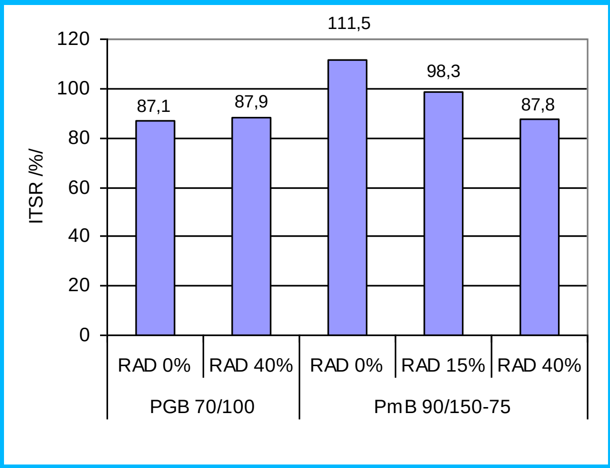


Figure 4.11 *ITSR* of SMA mixtures with different content of RAD

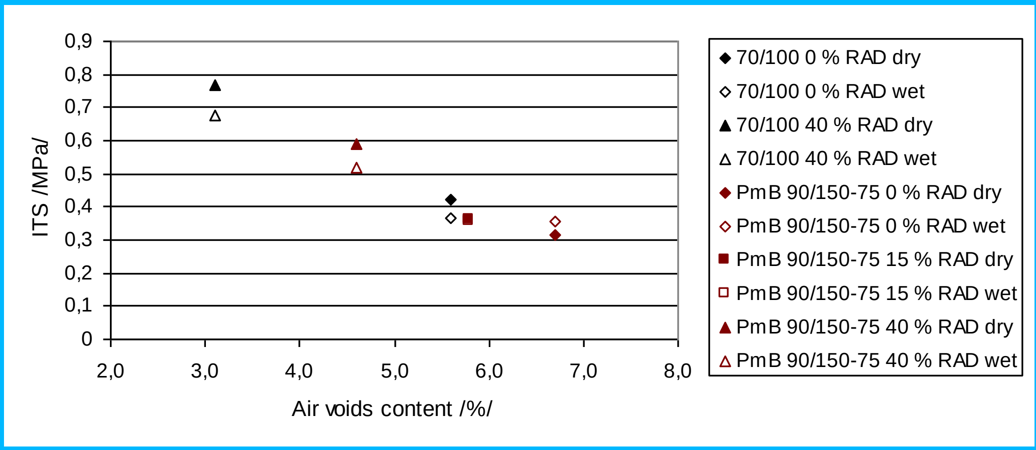
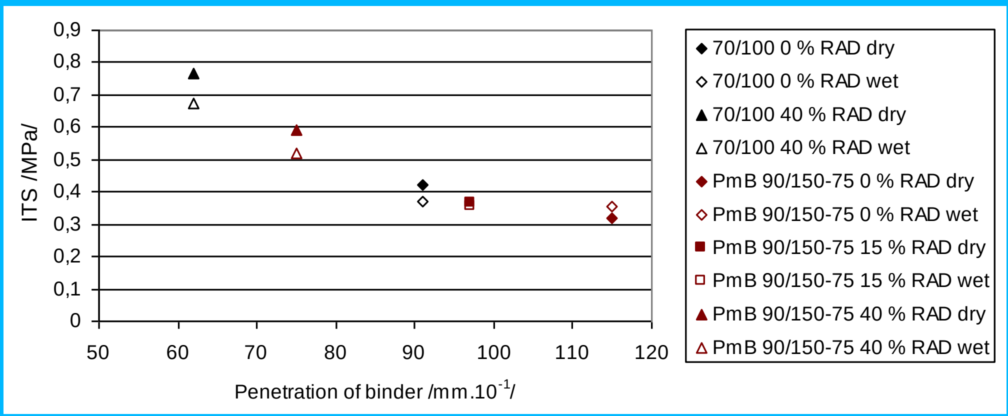


Figure 4.12 Relation between air voids content and *ITS* for SMA mixtures with different content of RAD



Note: The penetrations were adopted from the WP3 report for RAD binder content of 0 %, 15 % and 40 % although the real RAD binder content in the mixtures was 0 %, 14,6 % and 38,8 %.

Figure 4.13 Relation between penetration of binder and *ITS* for SMA mixtures with different content of RAD

The trend for *ITS* values for AC (see Figure 4.14) is similar to the values obtained for SMA. The higher content of RAS leads to higher values of *ITS*. It is valid for the dry and wet samples. The influence of air voids content and penetration of blended binder on the *ITS* values is shown in Figures 4.16 and 4.17 respectively. The *ITS* values decrease with increased air voids content in Figure 4.16 but only for the same type of virgin bitumen. If different binders are compared it can be seen that the value for the mixture Q8 + 0 % RAS is the lower compared to all values for the PMB virgin binder with all RA contents. The penetrations of blended binder can be used as an explanation (Figure 4.17). It is evident the penetration of blended binder in the mixture relates very well with the *ITS* values.

Regarding values of *ITSR*, they change with the content of RAS but the differences between mixtures with the same virgin binder are small, they are in the range of repeatability of the test. Moreover, the *ITSR* values are relatively high and it is no reason to suppose the addition of RAS has negative influence on water resistance of asphalt.

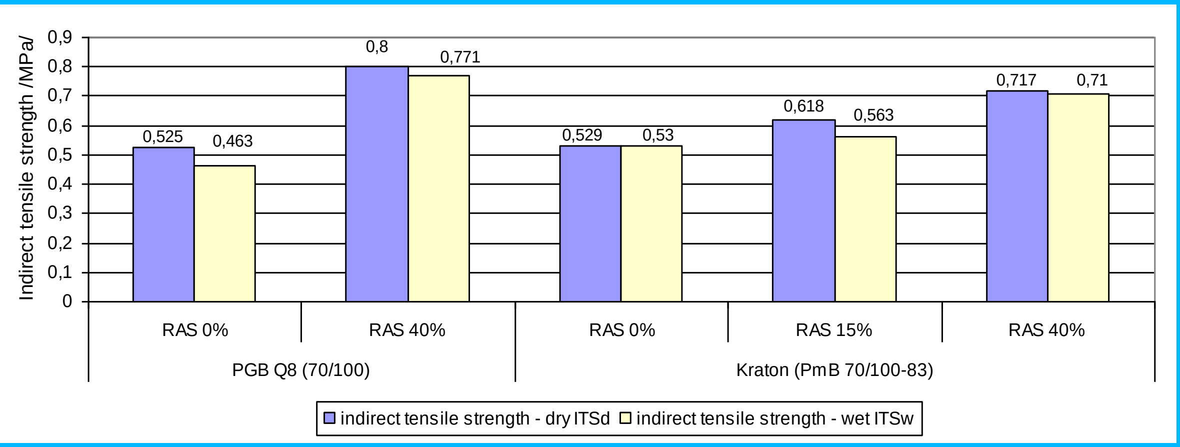


Figure 4.14 *ITS* of AC mixtures with different content of RAS

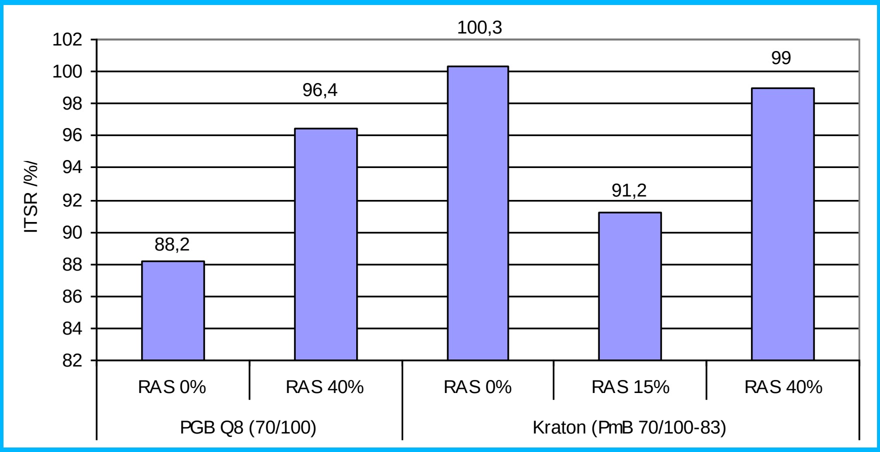


Figure 4.15 *ITSR* of AC mixtures with different content of RAS

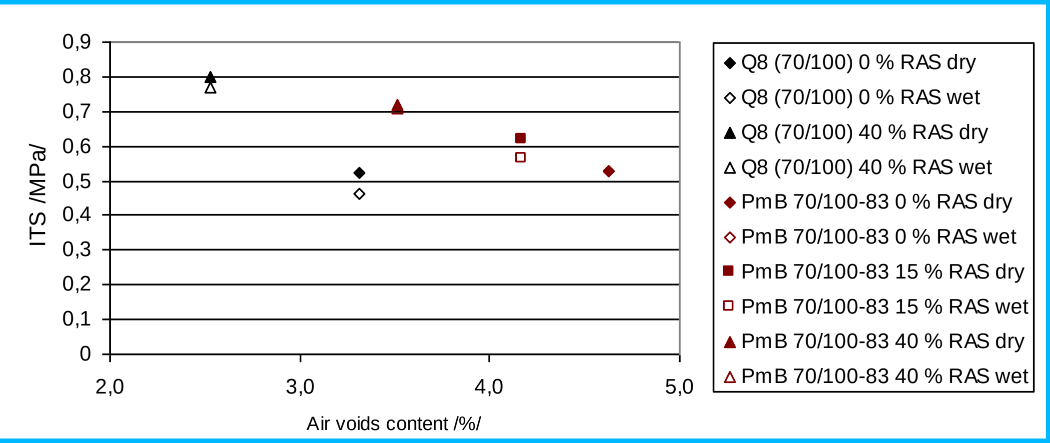
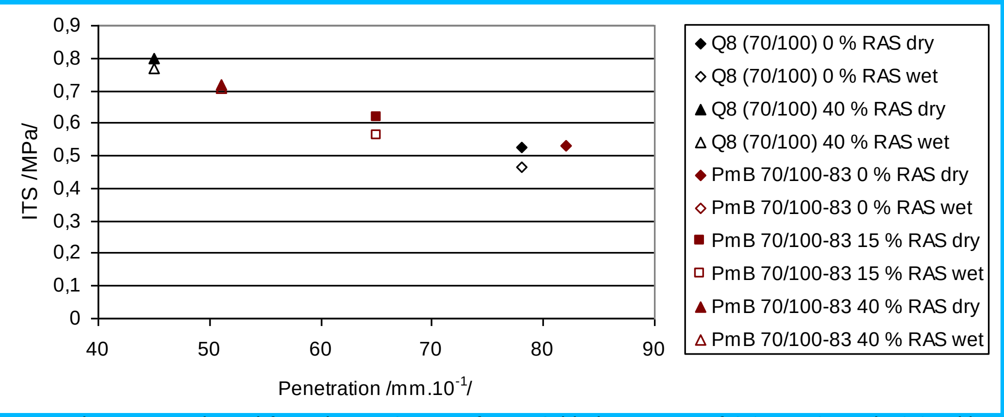


Figure 4.16 Relation between air voids content and *ITS* for AC mixtures with different content of RAS



Note: The penetrations were adopted from the WP3 report for RAS binder content of 0 %, 15 % and 40 % although the real RAS binder content in the mixtures was 0 %, 12,8 % and 34,1 %.

Figure 4.17 Relation between penetration of binder and *ITS* for AC mixtures with different content of RAS

The values of *ITS*, valid for PA, also increase with augmentation of RAN content regardless the type of binder (see Figure 4.18). But the positive influence of RAN addition does not relate to air voids content in this case. As it can be seen in Figure 4.20, relationship between air voids content and *ITS* is reversed for PA when compared to SMA or AC (higher *ITS* for higher air voids content). As PA has an extremely high void content it could be expected that normal trends with respect to air void content are not followed. However, data in the Figure 4.21 indicate the *ITS* of PA depend on penetration of blended binder and relationship between these parameters has the same tendency as for SMA an AC (i.e. lower penetration - higher *ITS*).

Similarly as for AC, the values of *ITSR* have small differences when the same type of virgin binder is used. Also, the values are very high and they prove addition of RAN has not any negative effect from water resistance point of view.

Some interesting facts can be observed in the case of PMB. The values of *ITSR* are higher than 100 % for all RAN contents (see Figure 4.19). It means the tensile strength of wet samples was higher in comparison with tensile strength of dry samples. A lot of factors can have an influence. One of them could be the type of used filer. Taking into account that the Wigro 60 K is limestone filler with 25 - 35 % hydrated lime, the results of *ITSR* on PA are in conformity with findings reported in others research. For example *ITSR* value larger than 100 % for porous mixtures with limestone filler is also reported in Giezen et al. (2012).

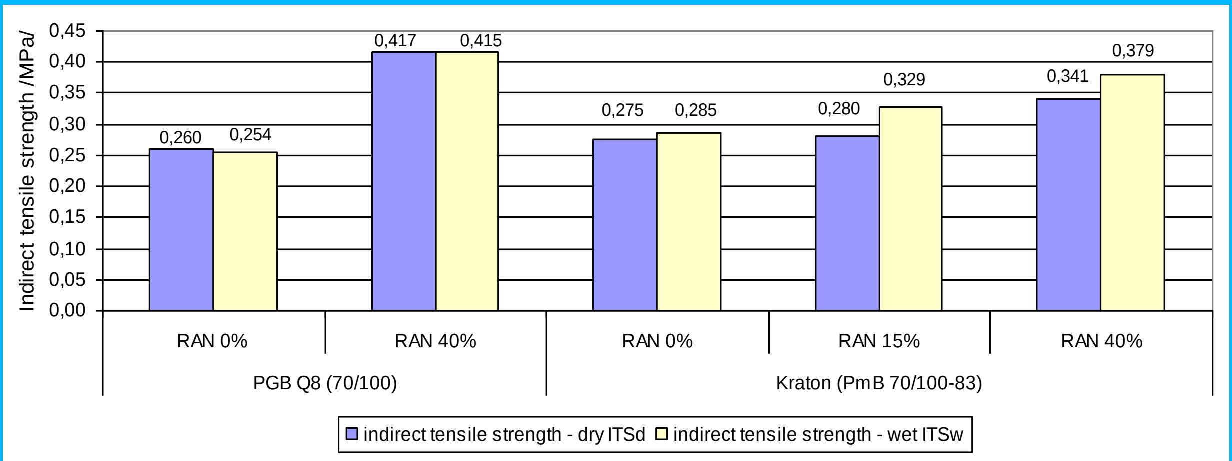


Figure 4.18 *ITS* of PA mixtures with different content of RAN

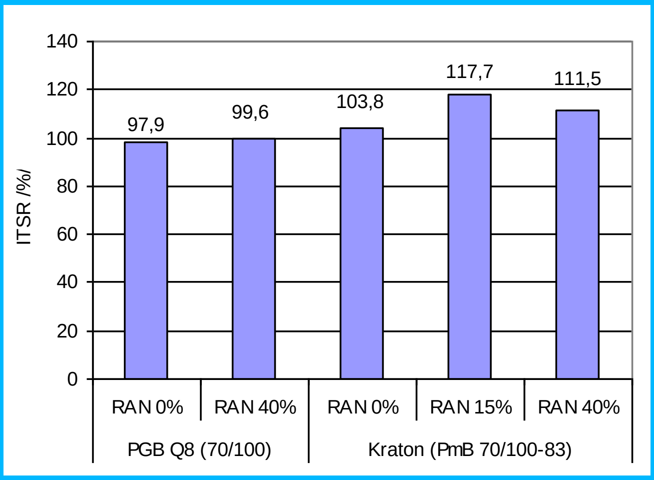


Figure 4.19 *ITSR* of PA mixtures with different content of RAN

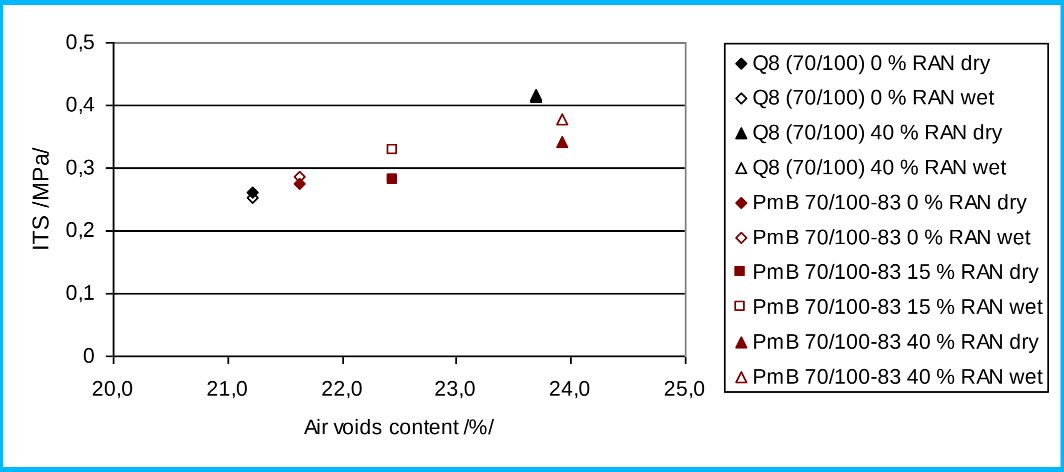
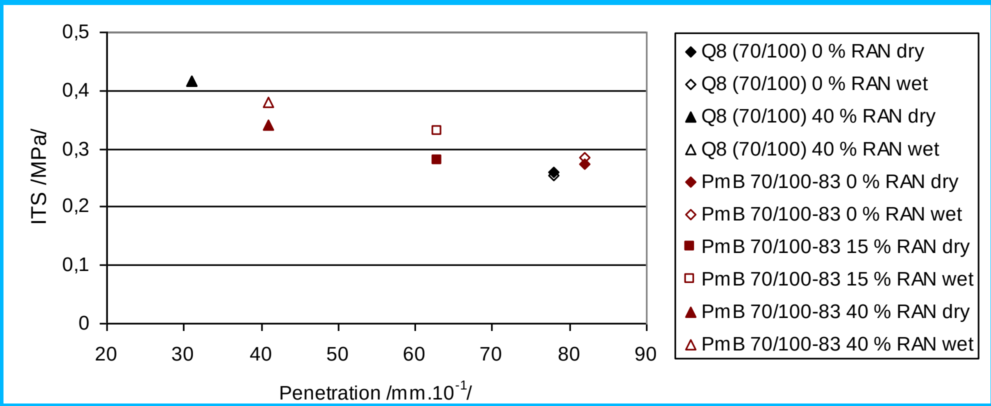


Figure 4.20 Relation between air voids content and *ITS* for PA mixtures with different content of RAN



Note: The penetrations were adopted from the WP3 report for RAN binder content of 0 %, 15 % and 40 % although the real RAN binder content in the mixtures was 0 %, 12,0 % and 31,8 %.

Figure 4.21 Relation between penetration of binder and *ITS* for PA mixtures with different content of RAN

Conclusions

The tests have proven the tensile strength of mixtures will be higher if RA is added. Two factors were confirmed as very important from stiffness point of view.

Penetration of blended binder plays role regardless of type of asphalt. More stiff binder (with lower penetration) has positive influence and increases stiffness of mixture. As binders in RA have obviously very low penetration, higher content of RA in a mixture can guarantee higher tensile strength of mix. On the other hand, it can lead to brittleness of blended binder at low temperatures. Therefore it is necessary to find a balance between needed tensile strength and a risk of brittleness taking into account temperature conditions at a locality where a mixture is intended to use. It can be verified by low temperature cracking and properties test according to EN 12697-46.

Air voids content, as second important factor, predetermines stiffness of dense graded asphalts. These mixtures are more resistant to break if air voids content is lower. On the other hand, it was found that tensile strength of PA mixtures has the inverse tendency (lower air voids content leads to lower tensile strength). When the mixtures are compared it is possible to say that small variable in air void plays a bigger role in the ITS for dense graded asphalt, rather than for porous asphalt.

For water susceptibility, both, ITSR and the absolute level of *ITS* must be considered. Regarding values of *ITSR*, they change with the content of RA but the differences between mixtures with the same virgin binder are small. Moreover, it was found the *ITSR* values are sufficiently high for virgin PGB and PMB. It can be assumed the addition of RA has no negative influence on water resistance of asphalt.

4.3 Wheel tracking test

Two main outputs of the wheel tracing test (WTS_{air} and PRD_{air}) are presented in Figures 4.22 and 4.23. Tests were carried out according to EN 12697-22 using the small device, method B, in air, at the test temperature of 50 °C.
Two different trends can be observed on Figures 4.22 and 4.23. There are relatively high changes for the mixtures with the virgin PGB and relatively consistent values if the virgin PMB was used.

The mixtures with the virgin PGB have the highest values, i.e. perform the poorest with respect to rutting resistance. But the 40 % addition of RA strongly improves the performance of mixtures with PGB to a comparable level of the mixtures with PMB at this content of RA (except of PA). Because each type of asphalt has basically the same aggregate gradation for the all contents of RA the properties of binders should be a reason of the improvement. Figure 4.24 and 4.25 shows the relationships between softening point of binder and characteristics of resistance to rutting. There is clear evidence the softening point of binder relates to values of WTS_{air} and PRD_{air}. Moreover, some difference between dense and open graded mixtures can be observed. Porous asphalt, as an open graded mix, has comparable parameters with SMA or AC for softening points above 75 °C. But there are higher WTS_{air} and PRD_{air} values for lower softening points when compared to the dense graded asphalts (SMA and AC).

There are small differences in the values of WTS_{air} and PRD_{air} on Figures 4.22 and 4.23 when PMB were used. The type of asphalt is not important in this case. Reason can be the softening points of blended binders are very close each other (see Figure 4.24) and all of them are high above the test temperature of 50 °C. Variation of the values can be connected with variability in material distribution in test samples and finally with repeatability of the test.

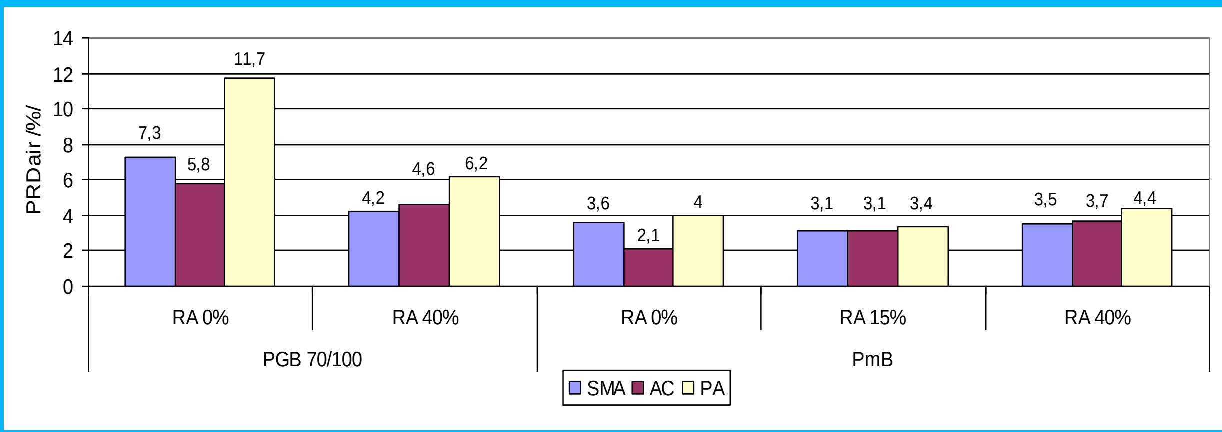


Figure 4.22 Results of PRD_{air} for all tested asphalts

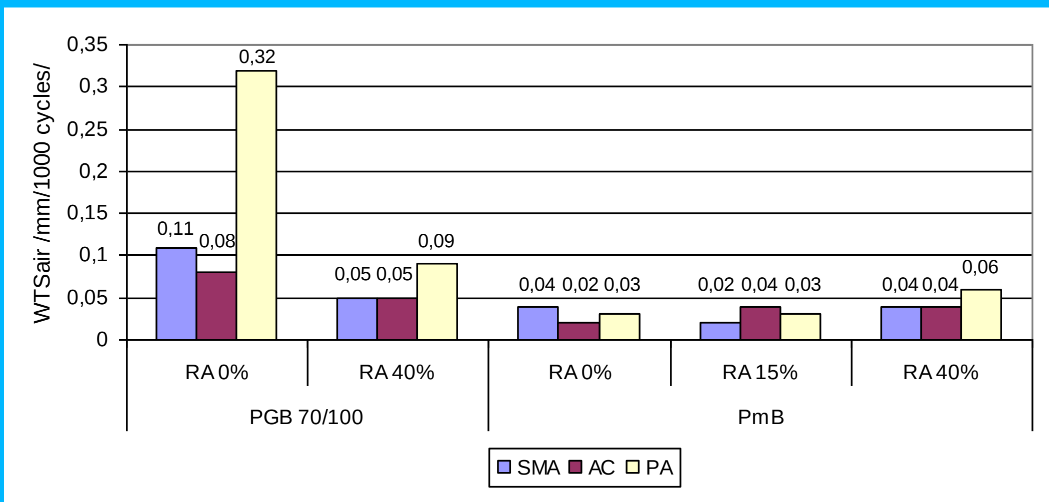
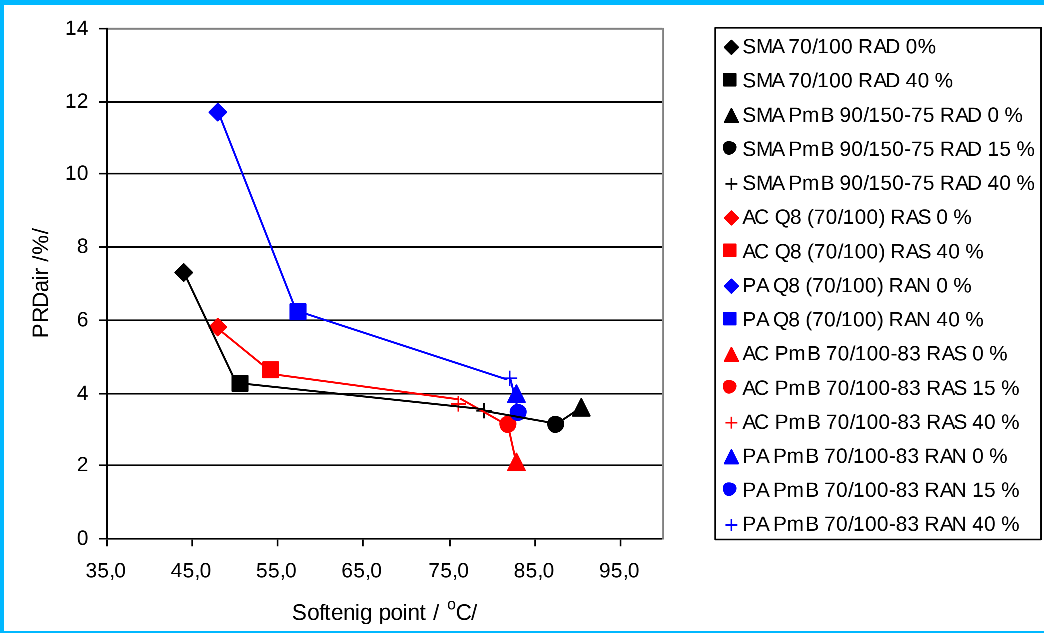
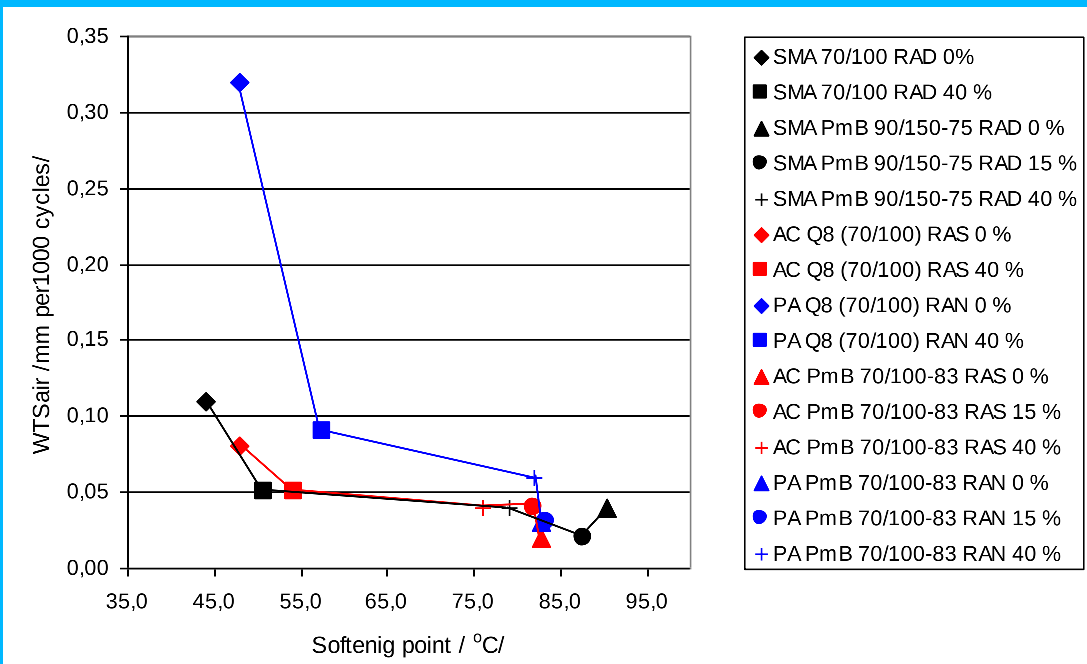


Figure 4.23 Results of WTS_{air} for all tested asphalts



Note: The softening point values were adopted from the WP3 report for RA binder content of 0 %, 15 % and 40 % although the real RAD binder content in the mixtures was 0 %, 14,6 % and 38,8 %, real RAS binder content was 0 %, 12,8 % and 34,1 % and RAN binder content was 0 %, 12,0 % and 31,8 %

Figure 4.24 Relationship between softening point and *PRD*air for all tested asphalts



Note: The softening point values were adopted from the WP3 report for RA binder content of 0 %, 15 % and 40 % although the real RAD binder content in the mixtures was 0 %, 14,6 % and 38,8 %, real RAS binder content was 0 %, 12,8 % and 34,1 % and RAN binder content was 0 %, 12,0 % and 31,8 %

Figure 4.25 Relationship between softening point and *WTS*air for all tested asphalts

Conclusions

It proved that the resistance of asphalts to rutting is strongly related to softening point of binder. It is desirable to use binders with the softening point at least 60 ^{o}C for wearing courses. Binders in a RA from old wearing courses have obviously relatively high softening point. Therefore RA can be added to a new mix without fear of drop in rutting resistance. On the contrary an addition of RA into a mix with a soft virgin PGB can improve the rutting resistance of asphalt. Any problem with rutting resistance was not noted when a RA was combined with a virgin PMB. Not even when RA content was 40 %.

Taking into account the results of test it is possible to suppose mixtures with a higher content of RA (up to 40 %) can reach the same parameters as mixtures without RA or with very low content of RA (less then 10 % of RA for wearing course mixtures). But it has to be ensured a blended binder will have a high value of softening point (at least 60 ^{o}C).

4.4 Stiffness

Stiffness of all mixtures was determined in accordance with EN 12697-26. The test method applying indirect tension to cylindrical specimens (IT-CY) was used. The tests were carried out at temperatures of -10 ^{o}C, 0 ^{o}C, +10 ^{o}C and +20 ^{o}C respectively. The results are shown in Figures 4.26 – 4.28.

Data in all Figures are in conformity with common knowledge, i.e. values of stiffness modulus are higher when temperature is lower. When the results for the same type of virgin binder are compared it can be observed the lowest values are for the RA content of 0 % and the highest for the RA content of 40 % (with a partial exception for the virgin PGB in PA). It means an addition of RA to virgin aggregate and binder increases stiffness modulus of mixture. Because aggregate gradation in the relevant type of asphalt is practically the same regardless RA content, according to general knowledge about virgin binders it can be assumed the stiffness of mixture should relates to stiffness of binder. Penetrations of binders, as the simplest representation their stiffness, were used to confirm the assumption. As can be seen in Figures 4.29 and 4.30 a relation between binder stiffness and mixture stiffness exists for all mixtures with the virgin PMB and also for the mixture with PGB + 40 % RA at -10°C. The same is valid for the mixtures with virgin PGB and both RA contents at the temperature of 20 ^{o}C.

Conclusions

It was proven that the penetration of the blended binders influences stiffness modulus of asphalt in the same manner as it is for virgin binders. Asphalt with a harder blended binder has higher stiffness modulus and vice versa. Penetration of binders in RA from old wearing courses is obviously lower then penetration of virgin binders used for wearing courses asphalts. Any addition of RA will decrease penetration of virgin binder and make asphalt stiffer. Required penetration of blended binder can be achieved not only by means of virgin binder but various RA content can be also used for this purpose (however, it is necessary to pay attention to possible brittleness of blended binder at high RA contents). All these things confirm positive influence on stiffness modulus of asphalt when RA is added into a mix.

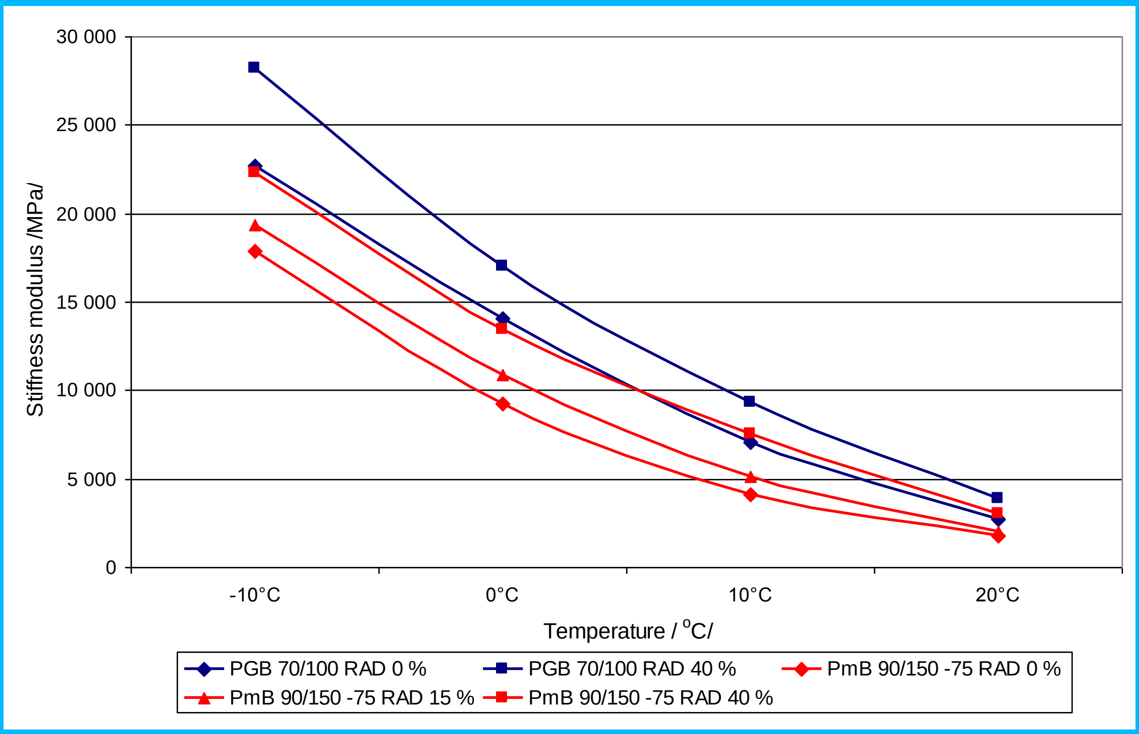


Figure 4.26 Stiffness modulus of SMA mixtures with different content of RAD

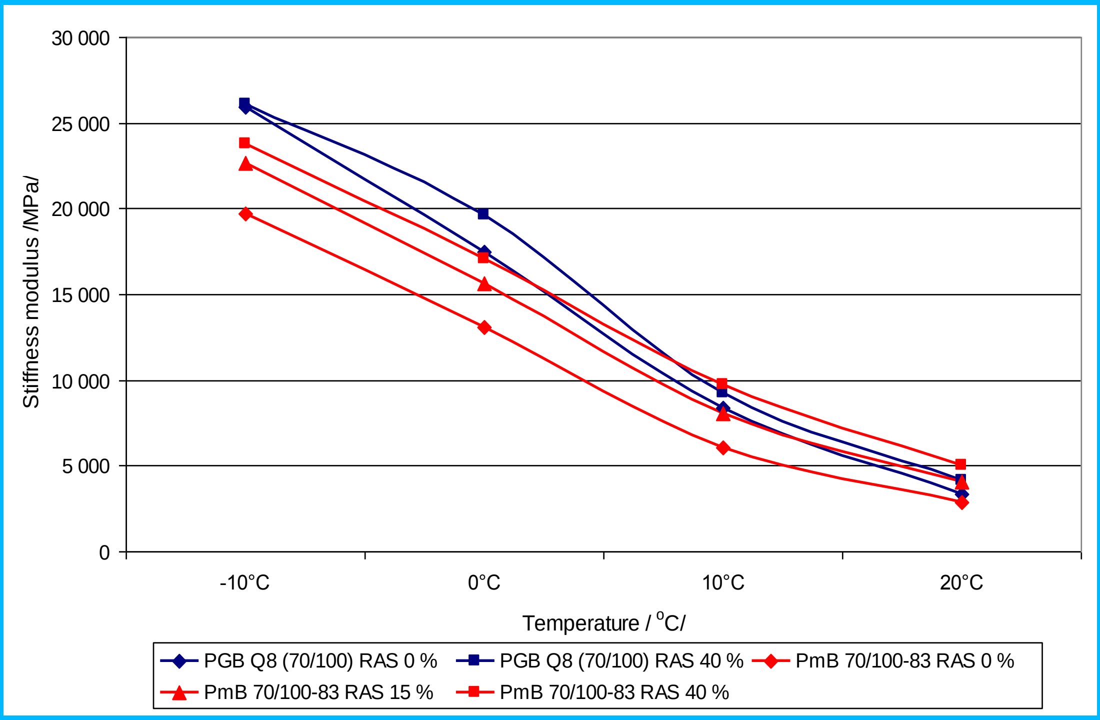


Figure 4.27 Stiffness modulus of AC mixtures with different content of RAS

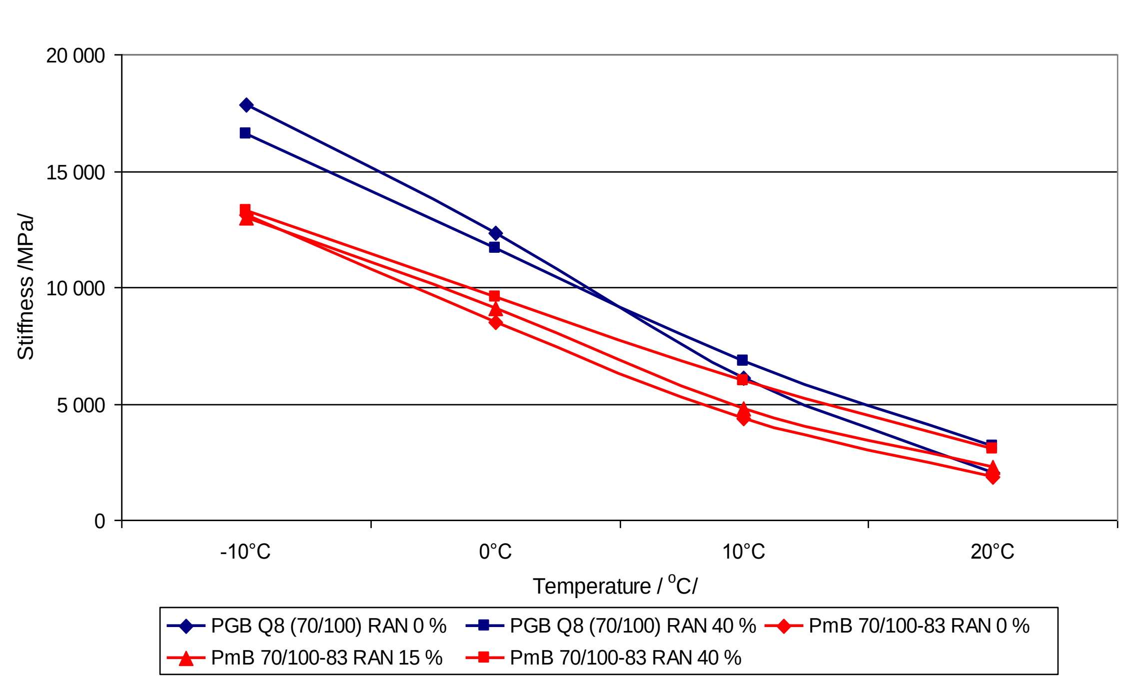
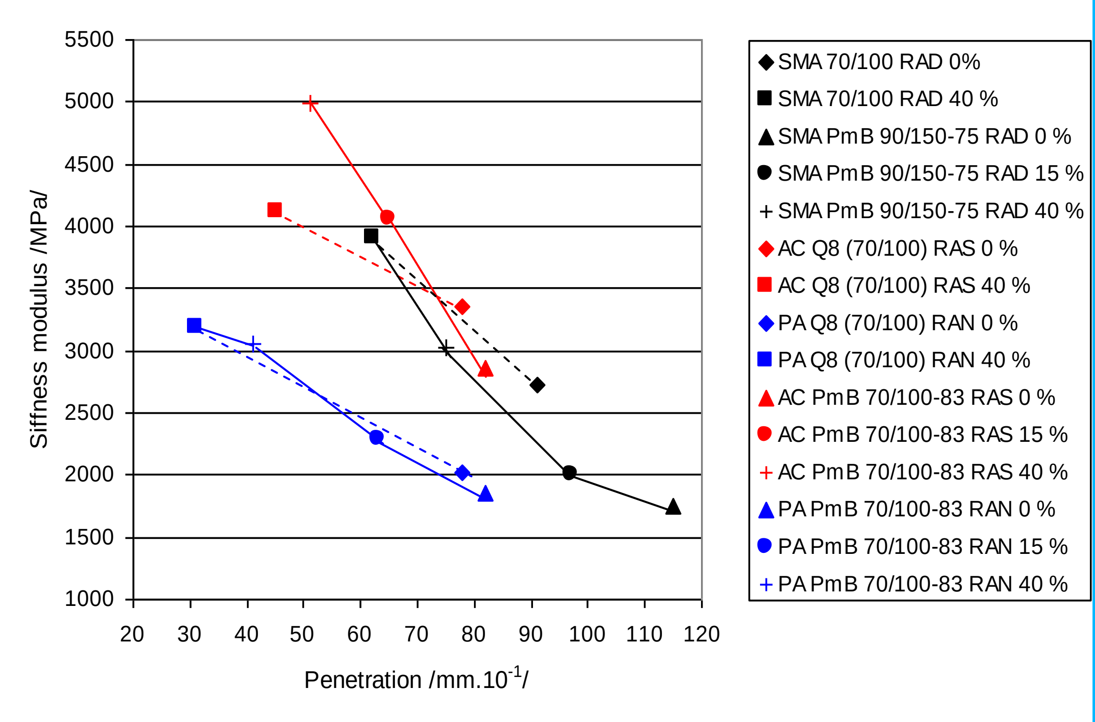
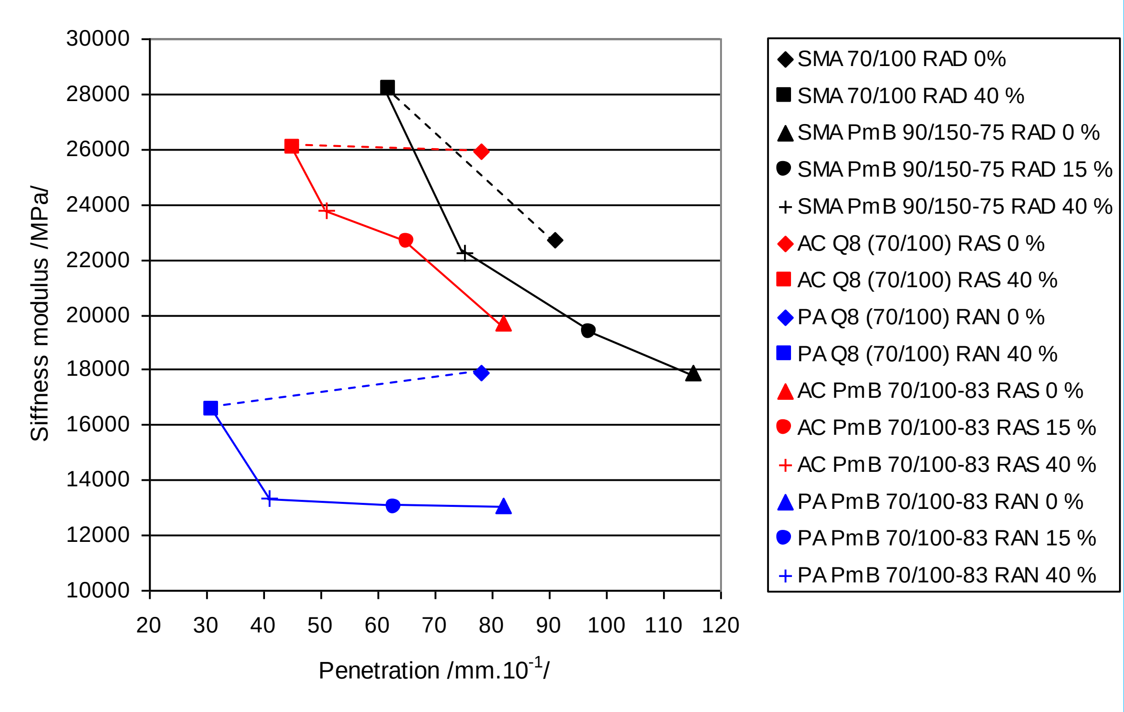


Figure 4.28 Stiffness modulus of PA mixtures with different content of RAN



Note: The penetrations were adopted from the WP3 report for RA binder content of 0 %, 15 % and 40 % although the real RAD binder content in the mixtures was 0 %, 14,6 % and 38,8 %, real RAS binder content was 0 %, 12,8 % and 34,1 % and RAN binder content was 0 %, 12,0 % and 31,8 %

Figure 4.29 Relationship between penetration and stiffness modulus for all mixtures at temperature of 20 °C



Note: The penetrations were adopted from the WP3 report for RA binder content of 0 %, 15 % and 40 % although the real RAD binder content in the mixtures was 0 %, 14,6 % and 38,8 %, real RAS binder content was 0 %, 12,8 % and 34,1 % and RAN binder content was 0 %, 12,0 % and 31,8 %

Figure 4.30 Relationship between penetration and stiffness modulus for all mixtures at temperature of -10 °C

4.5 Fatigue

The fatigue test results can be used to estimate the relative performance (fatigue life) of a mixture in the pavement. A chart of strain (or stress) versus number of load cycles to failure is used to determine the fatigue line of a mixture. The value ε_6 corresponding to 10^6 load cycles (strain at 10^6 load cycles) determined from the fatigue line is used to classify a mixture with respect to its fatigue performance. It is generally supposed that higher ε_6 values indicate a mixture with a larger fatigue resistance. However, the slope of fatigue line *b* is also important and can be used as a supplementary parameter for evaluation of the resistance against fatigue loading.

The results of the fatigue tests are in Table 4.1 and the fatigue lines for the individual AC mixtures are in Figures from 4.31 to 4.35. The comparison of fatigue lines of all five mixtures is shown in Figure 4.36.

It can be stated on the basis of the data in Table 4.1 and Figures 4.36 that if no RA is used, the use of a PMB binder, with a similar aggregate mix, results in a better fatigue resistance. The mixtures with virgin bitumen and without RA (A1 and A3) differ in ε_6. Both mixtures have standard course (slope) of fatigue line but the mixture A3 has higher value and thus it is more fatigue resistant. Moreover, all mixtures with virgin PMB (regardless RA content) shown a higher value of ε_6 compared to the mixtures with PGB.

It is evident from Table 4.1 and Figure 4.36 that addition of 40 % RAS into the mixture with virgin PGB increases the value of ε_6 significantly (from 87 to 130). It means mixture A2 (with 40 % RA) is more resistant to fatigue compared to the mixture A1. Moreover the slopes of the A1 and A2 fatigue lines are similar, so the difference in fatigue life between the mixtures A1 and A2 is expected to be the same for all levels of deformation. This improvement can be explained by the modification of virgin PGB via the added PMB originating from the RA. This would indicate that although the SBS content in the blended bitumen is lower compared to that of the PMB in RA (dilution of SBS through addition of PGB), it was sufficiently high to improve fatigue resistance. However part of the effect could also be explained by aging of the binder.

Table 4.1 The fatigue test results on the mixtures A1-A5

Mixture	ε_6	b [-]	r^2 [-]	S_N	$\Delta\varepsilon_6$	Category*
A1 (PGB + 0 % RA)	87,4	-0,21	0,955	0,143	4,61 E-10	$\varepsilon_{6\text{-}80}$
A2 (PGB + 40 % RA)	130,8	-0,18	0,782	0,355	2,83 E-09	$\varepsilon_{6\text{-}130}$
A3 (PMB + 0 % RA)	193,1	-0,13	0,573	0,448	4,41 E-09	$\varepsilon_{6\text{-}190}$
A4 (PMB + 15 % RA)	135,8	-0,08	0,707	0,568	1,32 E-09	$\varepsilon_{6\text{-}130}$
A5 (PMB + 40 % RA)	166,4	-0,04	0,804	0,612	1,24 E-09	$\varepsilon_{6\text{-}160}$

* According to EN 13108-1

It is observed that an addition of RAS into the mixtures with the virgin PMB resulted in a poorer fatigue performance compared to the mixture with virgin material. The poorer performance of mixture with RA can be concluded from the following observations:

- The value of ε_6 for mixtures A4 and A5 is lower compared to the reference mixture A3; it means the mixtures A4 and A5 are less resistant to fatigue compared to the A3 mixture.
- The slopes of the fatigue lines of the mixtures A4 and A5 are steeper when compared to mixture A3; this indicates that the mixtures with RA are more sensitive to the level of deformation

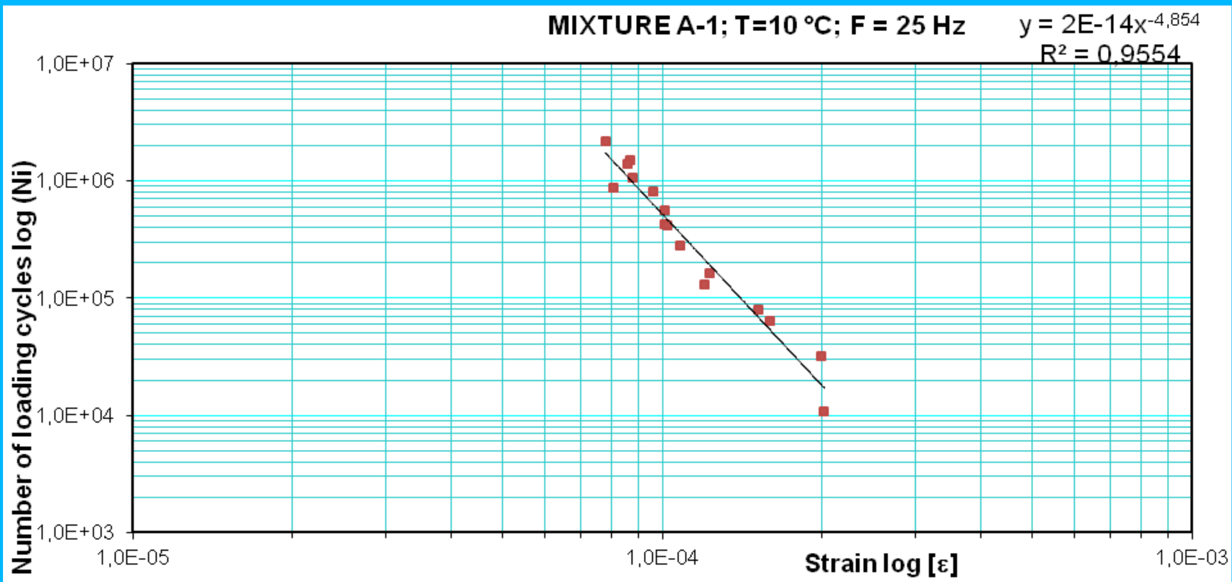
The lower value of ε_6 with addition of RA probably relates to the total SBS content in bitumen. The used virgin PMB contains 10 % of SBS (see p. 10, chapter 2.2) but PMB in RAS has lower SBS content (according to the results of WP3 report). When both bitumen are blended, the total SBS content in the mixtures A4 and A5 is lower compared to the mixture A3 (with pure virgin PMB). The lower level of modification leads to lower ε_6 and decreasing fatigue resistance of the mixtures A4 and A5. But there is a discrepancy between A4 and A5 values. It could be expected that the total SBS content in the mixture A5 should be lower then in the mixture A4 (because of higher RA content). Consequently the mixture A5 should be less fatigue resistant and have the lower ε_6. May be the homogeneity level of test results for the mixtures with PMB (see Table 4.1, the values of correlation coefficient r^2, standard deviation S_N, quality index $\Delta\varepsilon_6$) can be an explanation for this discrepancy.

Conclusions

It was demonstrated that there is an improvement in performance with respect to fatigue when a RA with PMB is added to a mixture with virgin PGB because an added PMB in RA modifies the virgin PGB (brings SBS into the blended bitumen). It was demonstrated that a relatively high content of RA of 40 % does not lead to poor performance from a fatigue point of view.

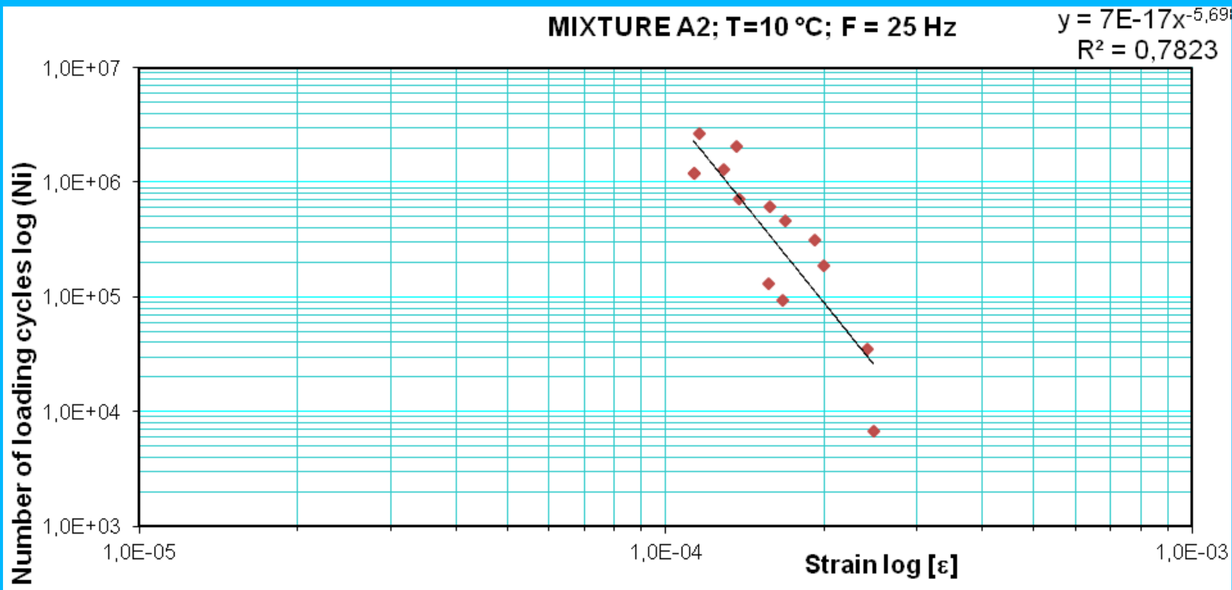
The fatigue tests also showed that if RA with a low modification level is added to a mixture with a highly modified bitumen, the fatigue resistance (fatigue life) of a mixture will be shorter.

This is probably due to a decreased SBS content in the blended bitumen. The lower level of modification leads to lower ε_6 and decreasing fatigue resistance of the mixture. Although the drop in fatigue resistance can be significant, all mixtures with the virgin PMB and various RA content show a higher fatigue resistance (have the higher value of ε_6) compared to the mixtures with virgin PGB.



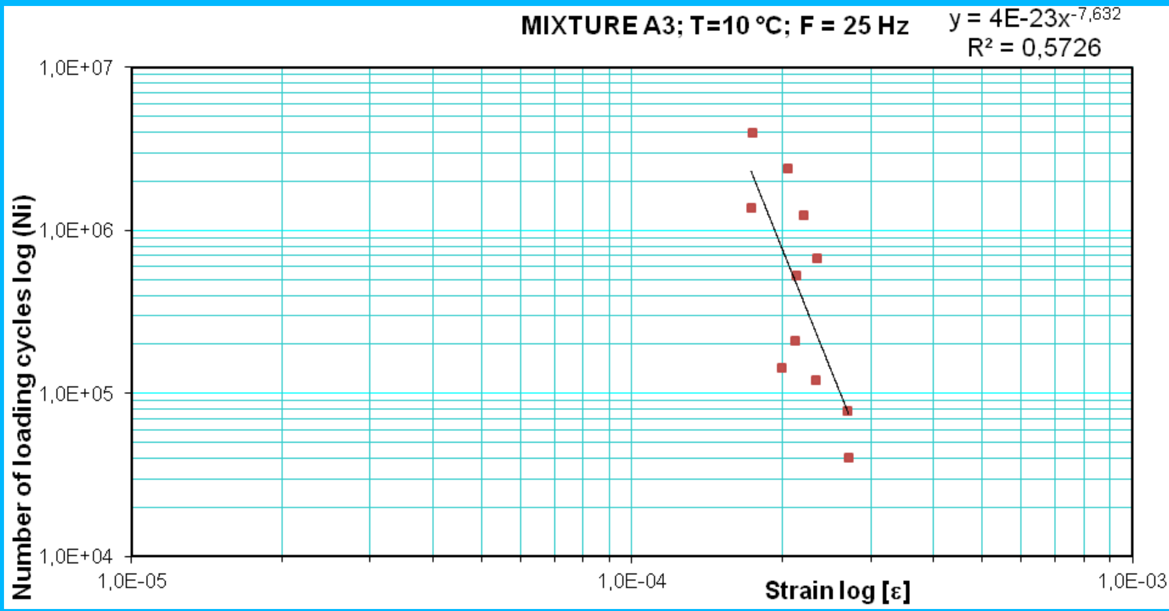
Parameters of the mixture A1	A_0	A_1	b	ε_6
	-13,70	-4,85	-0,21	87,4

Figure 4.31 The fatigue line of the mixture A1



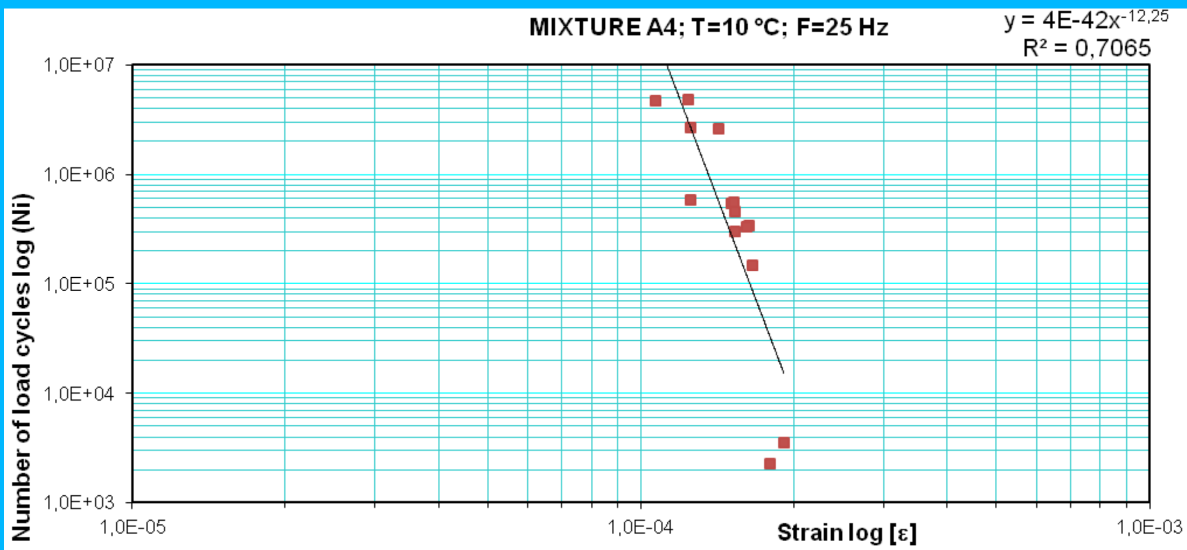
Parameters of the mixture A2	A_0	A_1	b	ε_6
	-16,13	-5,70	-0,18	130,8

Figure 4.32 The fatigue line of the mixture A2



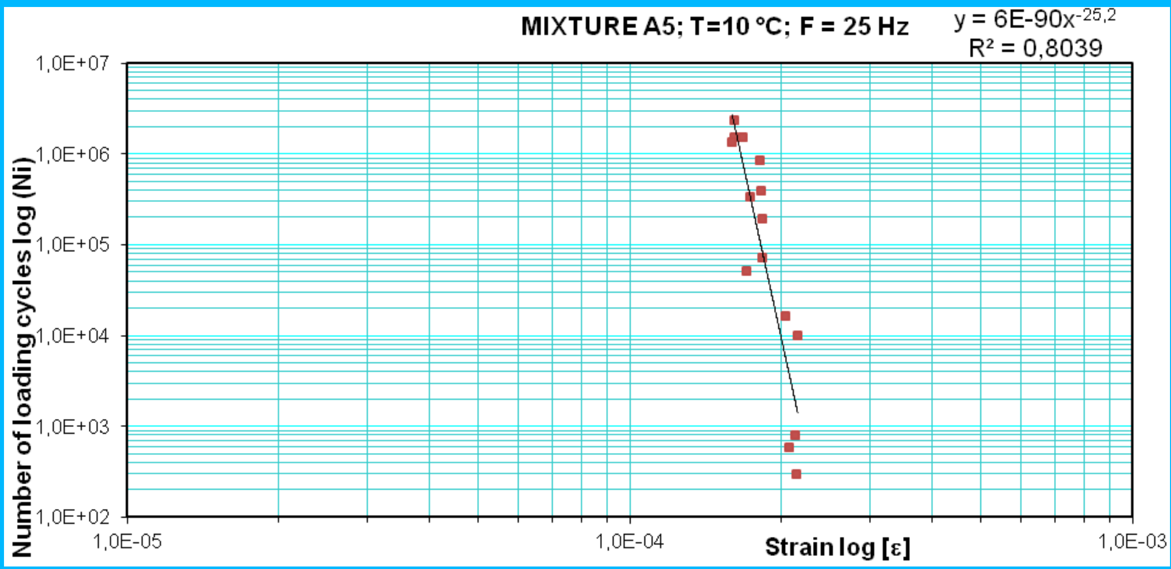
Parameters of the mixture A3	A_0	A_1	b	ε_6
	-22,35	-7,63	-0,13	193,1

Figure 4.33 The fatigue line of the mixture A3



Parameters of the mixture A4	A_0	A_1	b	ε_6
	-41,36	-12,25	-0,08	135,8

Figure 4.34 The fatigue line of the mixture A4



Parameters of the mixture A5	A_0	A_1	b	ε_6
	-89,21	-25,20	-0,04	166,4

Figure 4.35 The fatigue line of the mixture A5

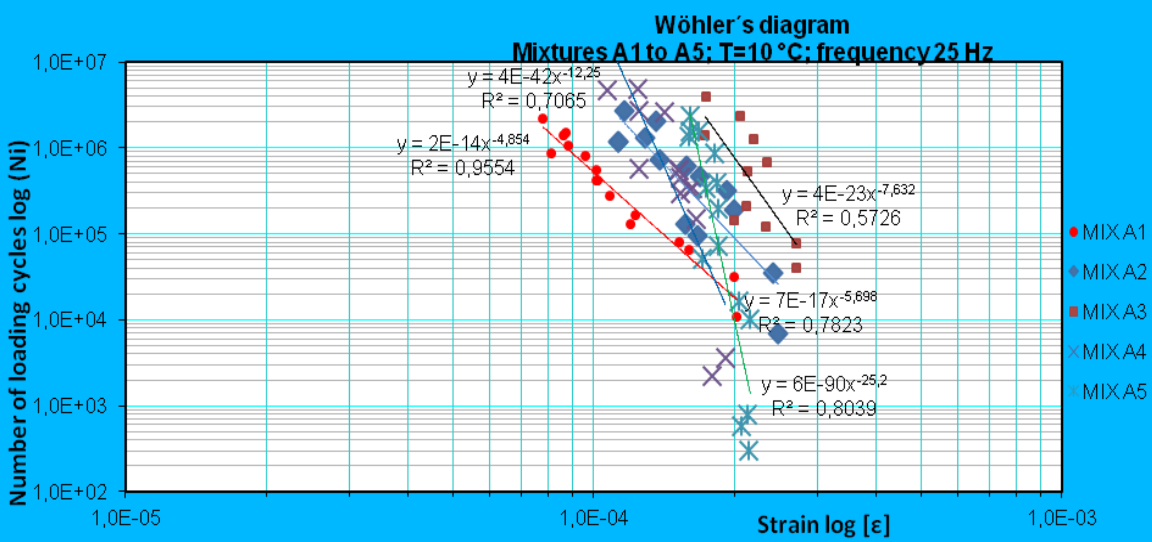


Figure 4.36 The fatigue line of all AC mixtures

5 Conclusions

A laboratory investigation was performed in order to study the effect of the use of polymer modified reclaimed asphalt on the properties that describe the performance of asphalt.

Three different types of frequently used asphalt mixtures for wearing courses in European countries (SMA 11, AC 11 and PA 8) were investigated under laboratory conditions. Reclaimed asphalt containing bitumen with SBS modification was combined with virgin material in the tested mixtures. The RA percentages of 0, 15 and 40 respectively were used in these mixtures. The virgin material consisted of PGB and PMB.

The result of laboratory investigation is as follows:

- The ITSR values for all mixtures meet the requirements (the lowest value for SMA11 is 87, 1 %, for AC11 88, 2 % and 97,9 % for PA8). This means that the water sensitivity of the mixtures containing RA is expected to meet the requirements for surface layers.
- The ITSR values also show a relation between the tensile strength and the penetration of the blended binder as measured in WP3. This relation indicates that the binder in the mixtures is blended to such an extent that it dominates the behaviour of the mixture.
- ITSR values for PA mixtures are very high (all higher than 100 %). This might be caused by the basic nature of the filler.
- The wheel tracking test showed no rutting for all polymer modified binders. The mixtures with RA showed a similar performance compared to the reference mixture.
- The mixture with paving grade bitumen and without RA showed a significant amount of rutting. The mixture with the paving grade bitumen and 40% RA showed a better performance with respect to rutting. This might indicate an advantage of the remaining SBS in the binder. However it should be noted that this could also be the effect of the aged binder which has a higher softening point.
- The mixtures with RA with PMB have a higher stiffness compared to the mixtures without RA. This could be an advantage because a larger stiffness means a higher bearing capacity. However if the stiffness is very high, this could lead to brittleness at low temperatures. Therefore it is necessary to find a balance between needed stiffness and a risk of brittleness taking into account temperature conditions at a locality where a mixture is intended to be used. It can be verified by low temperature cracking and properties test according to EN 12697-46.
- The mixture with the paving grade bitumen and 40% RA showed better fatigue parameters compared to the mixture with paving grade bitumen and no RA. On the contrary the mixture with virgin PMB was the most fatigue resistant and an addition of RA decreased fatigue performance and fatigue life. It seems that the SBS content in blended bitumen is an important parameter. Remaining SBS in RAS binder increased fatigue resistance of the mixture with PGB. Due to SBS content in RAS binder, the SBS content in the blended bitumen for PMB mixtures with RA was lower then SBS content in the virgin PMB and therefore the RA mixtures showed an inferior fatigue performance.

The influence of RA addition on properties of mixtures with respect to type of mixture, virgin binder and RA content is summarised in Table 5.1.

Table 5.1 Summary of RA addition influence

Mixture	Virgin binder	RA content	ITSd	ITSw	ITSR	Rutting resistance	Stiffness	Fatigue
SMA11	PGB	40 %	+	+	+	+	+	x
	PMB	15 %	+	+	-	=	+	
		40 %	+	+	-	=	+	
AC11	PGB	40 %	+	+	+	+	+	+
	PMB	15 %	+	+	-	=	+	-
		40 %	+	+	-	=	+	-
PA8	PGB	40 %	+	+	+	+	+ 1)	x
	PMB	15 %	+	+	+	=	+	
		40 %	+	+	+	=	+	

+ better than benchmark mixture (without RA)
- worse than benchmark mixture (without RA)
= comparable to benchmark mixture (without RA)
x not tested
1) only for temperatures above 0 °C

Although the test results give information about selected properties of mixtures with reclaimed asphalt containing PMB they may not be representative for all polymer modified mixtures because only limited number of mixtures (especially with respect to fatigue) were tested in the frame of the project.

6 References

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