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FIBRA

Fostering the implementation of fibre-reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use

Deliverable 5.1

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BAM

VEIDEKKE

University of Cantabria

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Fostering the implementation of fibre-reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use

Deliverable 5.1 – Scaling up of the production process and implementation of test sections.

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Executive summary

This report presents the laboratory and field-testing results and conclusions obtained during the scaling up of the production process and test sections' implementation of the fiber-reinforced asphalt mixtures studied in this project.

The production process of the asphalt mixes designed and evaluated at the laboratory in WP4 has been upgraded to the industrial scale by BAM and VEIDEKKE in the Netherlands and Norway respectively. The upscaling of the PA mixture was carried out by BAM and the upscaling of the AC mixtures was done by VEIDEKKE. In this document, the parameters affecting the mixing of the asphalt components (mixing sequence, temperatures, mixing times, etc) are defined and the results of the short-term performance of the mixtures and the identification of technical problems are presented.

The deliverable is divided into 5 chapters:

- CHAPTER1 consists on an introduction to the framework of the study;
- CHAPTER 2 presents the laboratory adaptation of the asphalt mixtures designed in WP4 to the specific requirements of the pilot section (type of mixture, materials, etc.);
- CHAPTER 3 shows the plant preparation and production trials carried out by BAM in the Netherlands;
- CHAPTER 4 presents the results and observations obtained during the asphalt mixes production and installation and during the evaluation of the test sections.
- CHAPTER 5 highlighted the most relevant conclusions and recommendations.

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1 Introduction

The CEDR Transnational Research Programme was launched by the Conference of European Directors of Roads (CEDR). CEDR is the Road Directors' platform for cooperation and promotion of improvements to the road system and its infrastructure, as an integral part of a sustainable transport system in Europe. Its members represent their respective National Road Authorities (NRA) or equivalents and provide support and advice on decisions concerning the road transport system that are taken at national or international level.

The participating NRAs in the **CEDR Call 2017: New Materials** are **Austria, Belgium-Flanders, Denmark, Germany, Netherlands, Norway, Slovenia, Sweden** and the **United Kingdom**. As in previous collaborative research programmes, the participating members have established a Programme Executive Board (PEB) made up of experts in the topics to be covered. The research budget is jointly provided by the NRAs as listed above.

The **objective of the FIBRA project** is to overcome the technical barriers for the safe and cost-efficient implementation of fibre-reinforced asphalt mixtures (FRAM) by NRAs with which an increase in the asphalt pavements durability could be achieved.

Despite the promising results achieved in previous research works and the availability of commercial fibres whose providers ensure a pavement life extension of at least a 50%1 and asphalt mixture life extension of around 200%2 (depending on the type of fibre and provider), the use of reinforced-asphalt mixtures is not as widespread as could be expected. This is principally due to the existence of gaps in the state of the knowledge that make National Road Administrations be reluctant to their incorporation.

In task 5.1 of the FIBRA project, the scaling up of the production process and the implementation of test sections have been carried out. The two wearing course mixtures, developed in task 4.1, have been produced at two different asphalt plants in two different countries: the production process of the PA mixture was adapted by BAM in the Netherlands and the production process of the AC mixtures was up-scaled by Veidekke in Norway. This has allowed the technology to the validated for the two type of mixtures (PA and AC), for two different asphalt plants and for two different countries, with different specifications and methods. **In this deliverable**, the conclusions obtained after the scaling up of the production process and the implementation of the test sections are presented including the parameters affecting the mixing, laying and compaction of the mixes as well as the identification of technical problems and potential barriers to the implementation of the technology by the NRAs.

The information to complete this deliverable has been obtained from the following documents included in the annexes:

- Report A73 combi-test section FIBRA 202001126. Produced by BAM.
- Internal report by Veidekke "Mix design for test section"
- Internal report by Veidekke "Test sections in Norway" with the results of the field trial.
- Internal report "information and data request for deliverable 5.1 and deliverable 5.4" completed by Veidekke and BAM.

2 Laboratory Research

2.1 Asphalt mixtures from WP4

The laboratory research carried out in WP4 was the base for the industrial upscaling. In this research, the impact of adding fibres in two type of asphalt mixtures (PA and AC) was evaluated. The results and conclusions of this study is included in deliverable D4.1.

POROUS ASPHALT (PA16):

In the case of PA mixtures, the final fibre selected was a blend of aramid and polyolefin fibres. A conventional 50/70 penetration grade bitumen was used with the experimental fiber-reinforced PA mixture (FRPA). On the other hand, a polymer modified bitumen and cellulose fibres were used in two additional reference mixtures to assess the impact of the fibres.

The main properties of the PA mixtures with the blend aramid/polyolefin fibres are presented in the Table 1. The fibres showed a very good performance in dry conditions, strengthen the mixtures and improving the behaviour of the reference mixture with conventional binder. In some cases, their impact was similar to the use of polymer-modified bitumen. However, their behaviour was worse in wet conditions. The fibres require to be well coated in order to avoid the water damage, so the percentage of bitumen need to be increased. This should not be a problem since the fibres are able to increase the anti-drainage capacity of the mixtures.

Table 1. Composition and mechanical performance of PA mixes (reference and experimental)

PA16		Ref 1	Ref 2	Ref 3	FRPA 1	FRPA 2
Bitumen / mixture (%)		4.5	4.5	5	4.5	5
Type of bitumen		50/70	PMB	50/70	50/70	50/70
Type of fiber		-	-	Cellulose	Aramid + Poliolefin	Aramid + Poliolefin
Fiber / mixture (%)		-	-	0.5	0.05	0.05
Voids test (EN 12697 – 8)						
Density (g/cm^3)		2.032	2.031	2.061	2.041	2.070
Voids (%)		21.4	21.4	19.2	21.1	20.4
Cantabro test in dry (EN 12697 - 17) & wet (NLT 362/92) conditions						
Dry (%)		15.0	10.6	11.4	12.5	7.9
Wet (%)		19.5	10.8	12.7	39.8	15.7
Water sensitivity test (EN 12697 – 12)						
I.T.S.	Dry (KPa)	982.2	1063.4	1046.8	1085.6	1159.8
	Wet (KPa)	771.1	979.5	981.7	931.9	988.6
I.T.S.R. (%)		79	92	94	86	85
Binder drainage (UNE-EN 12697 – 18)						
Draindown (%)		-	-	0.00	-	0.03

ASPHAL CONCRETE (AC16):

Two experimental mixtures were designed with the homopolymer polyacrylonitrile (panacea) synthetic fibre. In this case, the fibres modified the flow capacity of the mixtures increasing their resistance against plastic deformation. This let to increase the final quantity of bitumen used, improving the resistance against water damage and fatigue of the experimental mixtures. The composition and the mechanical performance of the reference and experimental mixtures is presented in Table 2.

Table 2. Compositions and mechanical performance of AC mixtures (reference and experimental)

		Ref	FRAC 1	FRAC 2
Bitumen / mixture (%)		4.3	4.3	4.6
Type of bitumen		50/70	50/70	50/70
Type of fiber		-	Polyacrilonitrile	Polyacrilonitrile
Fiber / mixture (%)		-	0.15	0.15
Voids test (EN 12697 – 8)				
Density (g/cm^3)		2.453	2.424	2.428
Voids in mixture (%)		5.1	6.2	5.6
Voids in aggregates (%)		15.3	16.3	16.4
Marshall test (EN 12697-34)				
Stability (kN)		15.7	16.2	15.9
Deformation (mm)		3.8	4.2	4.7
Water sensitivity test (EN 12697 – 12)				
I.T.S.	Dry (KPa)	1745.7	1708.0	1901,1
	Wet (KPa)	1610.0	1615.3	1745,8
I.T.S.R. (%)		92	93	92
Wheel tracking test (EN 12697 – 22)				
Slope (mm/1000 cycles)		0.10	0.03	0.03
Tracking depth (mm)		3.4	2.1	2.4

The results assessed by dynamic tests are presented in Table 3 and Table 4. Stiffness test (EN 12697-26. Annex B) and resistance to fatigue test (EN 12697-24. Annex D) were performed at 20°C. The fatigue test was performed at 30 Hz.

Table 3. Stiffness test of AC mixtures (reference and experimental)

	Reference		FRAC 1		FRAC 2	
Frequency (Hz)	Stiffness (MPa)	Phase Angle (°)	Stiffness (MPa)	Phase Angle (°)	Stiffness (MPa)	Phase Angle (°)
0,1	657	42,7	822	40,6	557	43,2
0,2	880	41,3	1068	39,6	742	42,3
0,5	1299	39,6	1567	38,0	1098	41,0
1	1712	37,9	1996	36,4	1468	39,3

2	2227	35,9	2568	34,6	1929	38,1
5	3095	32,8	3527	31,7	2748	34,7
8	3633	30,9	4104	30,0	3265	32,9
10	**3916**	**30,1**	**4421**	**29,4**	**3522**	**32,1**
20	4830	27,2	5448	26,6	4425	29,1
30	5516	26,0	5930	25,3	5067	28,1

Table 4. Fatigue test of AC mixtures (reference and experimental)

	strain-characteristic* (μm/m)	Fatigue line	R^2
Reference	142.3	$\varepsilon\,(m/m) = 4.791 \cdot 10^{-3} \cdot N^{-0.2645}$	0,96
FRAC 1	140.3	$\varepsilon\,(m/m) = 3.164 \cdot 10^{-3} \cdot N^{-0.2266}$	0.91
FRAC 2	160.8	$\varepsilon\,(m/m) = 2.417 \cdot 10^{-3} \cdot N^{-0.1962}$	0.98

*10^6 cycles

2.2 Laboratory adaptation to project (pilot) specifications

With the positive results of the laboratory tests, both the PA and AC mixtures developed in the laboratory are produced at two different asphalt plants in two different countries and are thereafter installed in pilot road sections. The fibre reinforced AC test section was constructed in Norway by VEIDEKKE together with her NRA Statens Vegvesen and the fibre reinforced PA test section was constructed in the Netherlands by BAM in collaboration with her NRA Rijkswaterstaat (RWS).

2.2.1 Porous Asphalt - The Netherlands (BAM)

As part of the FIBRA project, BAM and RWS have built a test section in the A73 in the last week of August 2020, to test the following mixtures:

- FIBRA 1, reference, conventional 2L-PA 8 mixture with PMB (Styrelf 65/105-80 A AP) produced at temperature of 185ºC.
- FIBRA 2, reference, 2L-PA 8 with penetration grade bitumen (70/100) produced at a temperature of 165ºC. This mixture comprises 0.2% cellulose fibre to prevent binder drainage.
- FIBRA 3, 2L-PA 8 with penetration grade bitumen (70/100) and 0.15% panacea fibre produced at a temperature of 165ºC.
- FIBRA 4, 2L-PA 8 with penetration grade bitumen (70/100) and 0.05% aramid fibre produced at a temperature of 165ºC.

Previously to the implementation, a laboratory research was conducted to design the 2L PA mixtures defined above and evaluate the performance of the mixtures containing fibre reinforcements in comparison to reference mixtures without fibre. All the mixtures were designed to equal the reference mixture, FIBRA 1, in terms of aggregate type (Bestone), gradation and bitumen content (5.3%). The only difference between mixtures is the type of bitumen and fibres if any. A complete Dutch standard type test for porous asphalt, including volumetric performance and water sensitivity performance was carried out.

In the Netherlands 2L-PA 8 is a mixture with a maximum grain size of 8mm that is widely used on the primary road network. This mixture is designed with 25mm thickness and design air voids of 23%. Compared with a traditional single layer PA 16, this mixture has a smaller grain size (8mm vs. 16mm) and slightly higher air voids (23 vs. 20.6%). Commonly an SBS polymer modified bitumen is used in PA 8.

Regarding FIBRA 3, Panacea is a trademark of a type of polyacrylonitrile fibre. According to experience of RWS-BAM and the CEDR FIBRA project, Panacea fibre with a length of 3.2mm is used in this research at an application rate of 0.15% (w/w) of the mixture. In addition, 0.15% cellulose fibre is added to the mixture to prevent binder drainage.

Concerning the aramid fibre, from the laboratory research carried out in WP4, four types of aramid fibres could be potentially used:

- 4A, Forta-FI: blend of aramid and polyolefins (1:7) with a length of 19mm, produced in US.
- 4B, Twaron 1080: Aramid fibre with a length of 6mm, produced in NL.
- 4C, Twaron 1095: Aramid fibre with a length of 1mm, produced in NL.
- 4D, Twaron 3500: Blends of aramid and polyolefins (4:6) with a length of 1mm, produced in NL.

For the selection of the aramid fibre to use in FIBRA 4, a stepwise laboratory research plan was followed. From this research that included a quickscan of the life cycle cost of all four fibres, Twaron 1080 was finally selected as reinforcement fibre in FIBRA 4 mixture. As in the case of panacea, 0.15% cellulose fibre is also added to the mixture to prevent binder drainage .For more information about the research plan and the laboratory results, see Annex 1.

EXPERIMENTAL RESULTS

As described in the project plan, the four FIBRA mixtures follow the same mixture design with Bestone 4/8 as the stone fraction. To determine the Bestone 4/8 application rate at which the design void ratio of 23% is obtained a mix design procedure is followed for the FIBRA 1 mixture. In this procedure, the FIBRA 1 mixture was made using three different percentages Bestone 4/8 in the mixture. These three laboratory produced mixtures were compacted by the use of the Marshall compactor giving 50 blows to each side of compacted tablets. Figure 1 gives the results of this mix design. As indicated a void ratio of 23% in the FIBRA 1 2L-PA 8, is obtained when the aggregate percentage is about 91.5%. This design parameter will be used for all four mixtures.

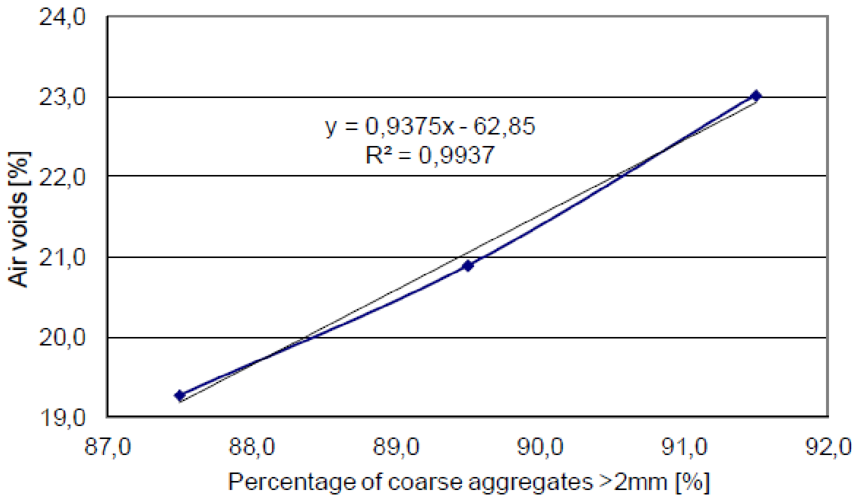

Figure 1. Results of mix design FIBRA mixtures

The final composition of the four mixtures is shown in Table 5. These mixtures are made without the need of fine aggregate or sand. Table 6 presents the practical parameters to be used for producing FIBRA mixtures.

Table 5. Final mixture compositions Fibre mixtures 1-4

Materials	FIBRA 1	FIBRA 2	FIBRA 3	FIBRA 4
	2L-PA 8 with PMB (1 KG)	2L-PA 8 PEN + cellulose (1 KG)	2L-PA 8 PEN + PAN (1 KG)	2L-PA 8 PEN + Aramid (1 KG)
Bitumen (kg)	0.0530	0.0530	0.0530	0.0530
Aggregate coarse fraction 4/8 (kg)	0.8910	0.8890	0.8880	0.8890
Aggregate fine fraction (kg)	0.0000	0.0000	0.0000	0.0000
Filler (kg)	0.0460	0.0460	0.0460	0.0460
Filler baghouse dust (Kg)	0.0100	0.0100	0.0100	0.0100
Fibre cellulose (kg)	0.0000	0.0020	0.0015	0.0015
Fibre (kg)	0.0000	0.0000	0.0015	0.0005
Type of aggregates (coarse)	Bestone (Norwegian sandstone)	Bestone (Norwegian sandstone)	Bestone (Norwegian sandstone)	Bestone (Norwegian sandstone)
Type of aggregates (fine)	Bestone (Norwegian sandstone)	Bestone (Norwegian sandstone)	Bestone (Norwegian sandstone)	Bestone (Norwegian sandstone)

Table 6. Practical parameters of FIBRA mixtures in laboratory research

	FIBRA 1	FIBRA 2	FIBRA 3	FIBRA 4
	2L- PA 8 PMB	2L-PA 8 Pen	2L-PA 8 Panacea	2L-PA 8 Aramid
Temperature of aggregates	180°C	155°C	155°C	155°C
Temperature bitumen	180°C	155°C	155°C	155°C
Temperature during mixing	180°C	150°C	150°C	150°C

Order of addition of the different materials	1. bitumen 2.aggregates	1. bitumen 2.aggregates 3. cellulose fibre	1. bitumen 2.aggregates 3. panacea fibre+cellulose fibre	1. bitumen 2.aggregates 3. aramid fibre+ cellulose fibre
Addition of the fibre (procedure, equipment)		Pre-dried Fibre added manually	Pre-dried Fibre added manually	Pre-dried Fibre added manually
Mixing times after the addition of the different material	After adding aggregates for about 60 seconds	After adding aggregates for about 20 seconds After adding fibres for about 40 seconds	After adding aggregates for about 20 seconds After adding fibres for about 40 seconds	After adding aggregates for about 20 seconds After adding fibres for about 40 seconds

Table 7 gives the results of the type testing of all four FIBRA mixtures. All the mixtures have similar volumetric properties and compaction performance with similar cycles of compaction using gyration compactor. The FIBRA 2, 3 and 4 show similar strength performance and the reference mixture FIBRA 1 shows a higher strength. The water sensitivity of FIBRA 1 and FIBRA 2 do not differ significantly. The ITSR water susceptibility of FIBRA 3 is 80% and that of FIBRA 4 is 77%. With this information, the next step was the plant production of the FIBRA mixtures.

Table 7. Results of laboratory type testing of all FIBRA mixtures

	FIBRA 1	FIBRA 2	FIBRA 3	FIBRA 4
	PMB	70/100	Panacea polyacrylonitrile	Twaron 1080 aramid
Gyrator cycles needed to reach air voids [-]	48	61	45	52
Air voids specimen	23.0%	22.8%	23.4%	23.5%
ITS dry [Mpa]	0.72	0.61	0.572	0.578
ITS wet [Mpa]	0.63	0.52	0.455	0.446
ITSR	88%	86%	80%	77%

2.2.2 Asphalt concrete - Norway (VEIDEKKE)

VEIDEKKE carried out the laboratory adaptation of the AC mixture designed in WP4 according to the materials, pilot section's requirements and the Norwegian standards and specifications. To do this, two AC mixes, AC11 and AC16 with pen bitumen (70/100) and fibres were designed and their performance compared with two reference mixes with pen bitumen (70/100) and PMB (60/105-60) as binders.

The mix-design was done according to the requirements in the Norwegian guidelines for asphalt pavements, for the grading curves of AC11 and aC16. The fiber content was fixed in

0.15% (w/w) according to the provider's recommendations.

The selection of panacea fibre to reinforce the AC mixture was carried out by all FIBRA partners in WP4.

EXPERIMENTAL RESULTS

The final composition of the four mixtures is shown in Table 8. These mixtures are made without the need of fine aggregate or sand. Table 9 presents the practical parameters to be used for producing FIBRA mixtures.

Table 8. Final mixture compositions Fibre mixtures A-F

Materials	A	B	C	D	E	F
	AC11 / 70/100	AC11 / 70-100 + Panacea	AC11 / PMB (60/105-60)	AC16 / 70-100	AC16 / 70-100 + Panacea	AC16 / PMB (60/105-60)
Bitumen (kg)	0.056	0.055	0.056	0.054	0.054	0.054
Aggregate (kg)	0.865	0.851	0.865	0.866	0.865	0.866
Filler (kg)	0.078	0.077	0.078	0.080	0.080	0.080
Fibre (kg)		0.0015			0.0015	
Type of aggregates	mylonite	mylonite	mylonite	mylonite	mylonite	mylonite

Table 9. Practical parameters of FIBRA mixtures in laboratory research

	A	B	C	D	E	F
	AC11 / 70/100	AC11 / 70-100 + Panacea	AC11 / PMB (60/105-60)	AC16 / 70-100	AC16 / 70-100 + Panacea	AC16 / PMB (60/105-60)
Temperature of aggregates	160	160	175	160	160	175
Temperature bitumen	160	160	175	160	160	175
Temperature during mixing	160	160	175	160	160	175

Order of addition of the different materials	1. Aggr. 2. Filler 3. Bit.	1. Aggreg. 2. Filler 3. Fibre 4. Bitumen	1. Aggreg. 2. Filler 3. Bitumen	1. Aggreg. 2. Filler 3. Bitumen	1. Aggreg. 2. Filler 3. Fibre 4. Bitumen	1. Aggreg. 2. Filler 3. Bitumen
Addition of the fibre (procedure, equipment)		Manually			Manually	
Mixing times after the addition of the different material	Total mixing time 120 seconds	Total mixing time 150 seconds	Total mixing time 120 seconds	Total mixing time 120 seconds	Total mixing time 150 seconds	Total mixing time 120 seconds

Table 7 gives the laboratory results of the A-F mixtures. The Marshall values are about the same level, or slightly better, for the AC-mixes containing fibres compared with the mixes without fibres. The deformation properties evaluated using wheel-tracking tests, are better for the AC mixes with fibre compared with the mixes with 70/100 bitumen. Mixes with PMB gave the best results, both for Marshall and wheel tracking test.

Table 10. Results of laboratory testing of all A-F mixtures

	A	B	C	D	E	F
	AC11 / 70/100	AC11 / 70-100 + Panacea	AC11 / PMB (60/105-60)	AC16 / 70-100	AC16 / 70-100 + Panacea	AC16 / PMB (60/105-60)
Marshall test						
Marshall stability (kN)	7.8	7.6	10.3	8.9	9.5	11.8
Marshall flow (mm)	3.2	3.1	3.2	3.5	3.4	3.8
Marshall quotient	2.4	2.5	3.2	2.5	2.8	3.1
Void content of Marshall samples (mean value)	3.9	3.9	3.1	2.5	2.3	4.6
Wheel tracking test						
WTSair	0.111	0.097	0.029	0.175	0.101	0.031
PRDair (mm)	3.3	2.9	1.4	4.5	3.4	1.6
RDair (%)	6.6	5.7	2.9	9.1	6.7	3.1

3 Plant preparation and production trials

3.1 2L Fiber-reinforced Porous Asphalt - The Netherlands (BAM)

3.1.1 Research plan

In advance of production and installation of the test sections, BAM carried out a set of production trials were done that included different necessary arrangements and tests. It should be noted that the application of fibres might involve certain risks. Potential risks and possible solutions are listed below:

a. Binder drainage

The synthetic fibres are used in PA as reinforcement. For bitumen/mortar rich PA mixtures mortar drainage forms a potential risk. To ensure ample resistance to binder drainage some extra % of cellulose fibre had to be used in combination with the synthetic fibre. In practice, two steps can be followed for examining binder drainage performance of synthetic fibres in porous asphalt. Step one is to conduct a laboratory binder drainage test. Step two is to simulate the transportation process by means of plant trials. In this research, the plant produced asphalt mixtures were loaded into a truck for a transport simulation of 1 hour to verify that the issue of binder drainage is solved by the application of the cellulose fibre.

b. Inhomogeneity

The use of synthetic fibres in PA can cause problem such as inhomogeneity. At the production plant, the fibres are added manually into the mixer by use of low melt bags. Due to the nature of the fibre there is a chance that the fibres distribute inhomogeneously in the mixture. As such, it is important to carry out a plant production trial to visually inspect the homogeneity of the fibre distribution in the mix.

c. Possible influence of laying and compaction

For the use of fibres in Porous Asphalt, PA, it is very important to understand the possible influence on the laying and compaction process. In this research, a plant installation trial was carried out at the asphalt plant using a paver with a 5 m screed over a length of 50 meter to evaluate this.

Due to the inexperience of BAM with the production and installation of the FIBRA 4 mixture (Aramid fibre reinforced 2L PA8), production trials of this mixture were carried out on 21st August 2020.

The plan of the plant trials is given in Table 11. During these trials, about 30 ton (10-12 charge) of the FIBRA 4 2L-PA 8 Aramid mixture was produced. Mixture samples were collected for further laboratory research, e.g. composition and compaction. The produced mixture was loaded into a truck for a 1-hour transport simulation to evaluate possible draindown. After that the mixture feed to the paver for installation in a trial test section on the asphalt plant yard. During this of the workability, compactability and temperature was monitored. Interviews with members of the installation teams were conducted for first impression of this material. Water drainability test (Becker Test) and coring were done one day after installation. From the core specimen information about realized thickness was evaluated.

Table 11. Overview of plant preparation and production trials

Phase 1	**Production trials**	FIBRA 4: 2L-PA 8 Aramid
1.1	Preparation and quality control of bitumen, fibres and additives	
1.1.1	*Pen & Softening point*	*1x PMB* *1x 70/100 pen bitumen*
1.2	Production trials	
1.2.1	*Production and construction*	*50ton*
1.2.2	*Gradation and bitumen content plant mix*	*2x*
1.2.3	*Lab compaction gyrator*	*2x*
1.2.4	*Temperature evaluation*	*1x*
1.2.5	*Laying evaluation*	*1x*
1.2.6	*Compaction evaluation*	*1x*
1.2.7	*Becker test*	*3x*
1.2.8	*Thickness from cores*	*3x*

3.1.2 Results of production trials

MIXING PROCESS

During the trial production, special attention was given to the mixing process of mixtures with synthetic fibres. The experience of handling panacea fibres helped with handling aramid fibres. As shown in Figure 2, the aramid fibres were packed into a low melt bag with a constant weight of 1.5 kg for a batch mixing of 3000 kg mixture (addition of 0.05%). The synthetic fibres are manually fed into the mixer after the aggregates. The cellulose fibre was added automatically into the mixer using mechanical blowing. The mixing time of the fibre reinforced mixture was slightly increased with 5 second to ensure proper dispersion of the fibres in the mixture. The main parameters used in the production process of FIBRA 1 and FIBRA 4 is shown in Table 8.

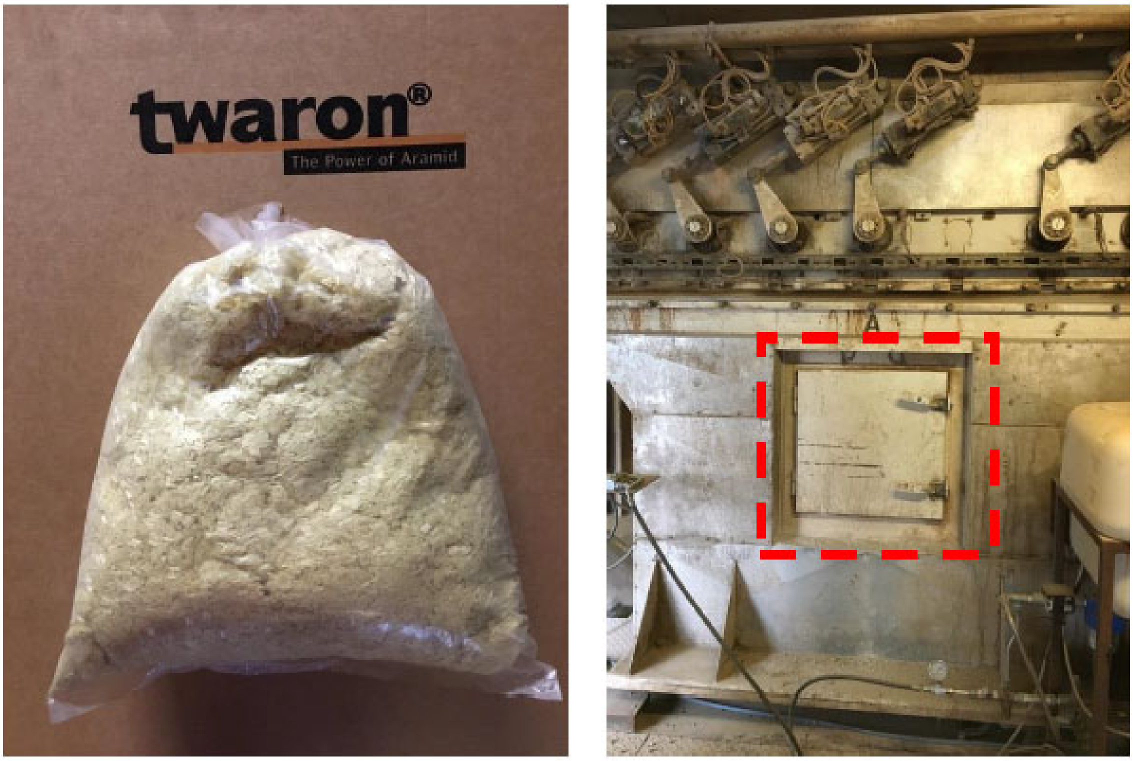

Figure 2. Example of aramid fibres in low-melt bag (left) and the inspection opening of the mixer (right) used to manually insert the bags into the mixer

Table 12. Production process of reference and experimental mixtures at the asphalt plant

	FIBRA 1	FIBRA 4
	2L- PA 8 PMB	2L-PA 8 Aramid
Temperature of aggregates	224°C	204°C
Temperature bitumen	180°C	155°C
Temperature during mixing	181°C	165°C
Order of addition of the different materials	1. aggregates 2. filler 3. bitumen	1. aggregates 2. aramid fibre+cellulose fibre 3. filler 4. bitumen
Addition of the fibre (procedure, equipment)		Cellulose fibre was added automatically by blowing Aramid fibre was added manually using low-melt bag in the mixer
Mixing times after the addition of the different material	after adding all materials mixing for 25 seconds	after adding all materials mixing for 30 seconds

MIXING PERFORMANCE

The results of the production control of the trial production are shown in Table 13 and summarized as follows:

- The composition of the material in charge 3 and in the hopper hardly differ, indicating that no significant variation in material composition occurs during production and 1 hour transport.
- The percentage passing 5.6 mm is on average 35%, significantly lower than that of the type test. It has to be noted that the produced FIBRA mixture has only 1 type of coarse fraction Bestone 4/8 and has no sand. The grading of the mixture is solely dependent on the grading of the aggregates Bestone 4/8.
- The percentage passing 2 mm, which is closely related to the air voids content of the mixture is under control.
- The bitumen content is around 5%, which is within production limits.
- Due to limited production amount, the mixture temperature was approximately 180°C, 25°C higher than required. This is non-favourable for the mix (Short Term Aging), but is good for practical evaluation, e.g. binder drainage. Combined with the first observation on gradation, it can be seen that this mixture has no issues of binder drainage.
- The results of the laboratory compaction show that the air voids of the mixture from both Marshall and gyrator are on the higher side than that of the Type Test mixture.

Table 13. Production control of trial production of FIBRA 4 mixture

Sieve passing	#1 Charge 3	#2 In hopper	Average	Type Test	Minimum	Maximum
11.2 mm [%]	100.0	100.0	100.0	100.0		
8 mm [%]	88.8	88.5	88.65	89.3	86.3	92.3
5.6 mm [%]	33.6	36.5	35.0	41.6	38.1	45.1
4 mm [%]	14.1	15.5	14.8	17.1		
2 mm [%]	7.2	8.0	7.6	8.5	6.0	11.0
0.5 mm [%]	6.3	6.7	6.5	6.5		
0.063 mm [%]	6.0	6.0	6.0	6.0	5.4	6.6
Bitumen content [%]	5.0	5.0	5.0	5.3	5.0	5.6
Mixture temperature [°C]	182		182	155	140	170
Density Marshall compaction [kg/m^3]	1889		1889	1913		
Air voids Marshall compaction [%]	24.4		24.4	23.0		

Density Gyrator compaction [kg/m³]	1833		1833	1862		
Air voids gyrator compaction [%]	26.7		26.7	25.1		

PLANT CONSTRUCTION TRIALS

Figure 3 illustrates the location of the trial sections next to the asphalt plant with 2 sections with a combined width of 6m and a length of 50 meter. During the trial production and installation different process parameters on laying and compaction were investigated. After installation, interviews with the installation crew, water drainability and cores were taken to evaluate the applied laying and compaction strategy. Combination of these two results, a final laying and compaction strategy for this mixture can be made.

Figure 4 and

Table *14* present the results of the plant installation trials. The following can be observed about the plant installation trials,

- The installation of the FIBRA 4 mixture by the installation team of the A73 test sections went smoothly.
- The trial installation gives the team also a first feel for the mixtures to be constructed in A73. The whole team was interviewed after the construction. According to the team the FIBRA 4 mixture is easier to handle with handwork and has less emission. There is almost no influence on the machinery laying and compaction.
- The compacted FIBRA 4 mixture is homogenous, no fat spot is noticed.
- The trial section shows good water drainability. Becker tests indicate an outflow time of around 10 second on average, lower than that of the Dutch standard for 2-layer porous asphalt of maximum 17 second on average and maximum 20 second of individual measurement.
- The thickness of the FIBRA 4 layer top layer is about 29 mm, which fulfils the requirement of 25 mm.
- The measurement of air voids of individual layers of 2-layer porous asphalt is not accurate according to the Dutch standard due to the open structure and the small thickness. As a result, the measured air voids are only indicative. In this section, an air voids average of 27.5% of the top layer is found.

Figure 3. Plant construction site during plant trials

Figure 4. Illustration of core samples from plant construction trials

Table 14. Resutls of plant construction trials

Nr.	Nuclear total layers		Water drainability	Thickness			Air voids top layer (indicative) [%]
	Density [kg/m3]	Air voids [%]		Underlayer [mm]	Top layer [mm]	Total [mm]	
A1	1932	22.3	10.3s	51	28	79	
A2	1900	23.5	11.1s	45	28	73	26.4
A3	1929	22.3	9.4s	40	33	73	27.6
A4	1893	23.8	10.0s	50	32	82	27
A5	1812	27.1	12.3s	42	28	70	26.4
A6	1851	25.5	9.3s	42	28	70	26.5
A7	1913	23.0	10.8s	55	30	85	
A8	1880	24.3	10.8s	42	28	70	31.3
A9	1851	25.5	9.4s	45	28	73	
Average	1885	24.1	10.14s	46	29	75	27.5
Requirement			Average ≤ 17s Individual ≤ 20s	45 mm	25 mm	70 mm	

3.1.3 Summary plant trials

The following can be summarised from the plant production and installation trials:

- The FIBRA 4 mixture with aramid fibre can be produced in the plant without difficulty. The fibre can successfully be fed manually into the mixer using the inspection opening and a pre-packed low-smelt bags.
- The produced FIBRA 4 mixtures are homogenous with limited variation. The production temperature is around 180ºC due to limited production amount. No segregation or binder drainage is observed during production and also after the simulation of 1-hour transport.
- The produced FIBRA 4 mixtures are slightly more porous than the laboratory produced mixtures.
- The construction of FIBRA 4 mixture can be carried out with regular equipment and the installation strategy of standard 2L-PA 8. The workability of the FIBRA 4 mixture is better than that of the standard 2L-PA 8 with PMB, FIBRA 1.
- The constructed trial sections at the plant yard have good water drainability and proper layer thickness.

As a result, it is concluded that the plant trials are successful and enough information is obtained for installation of the test sections in the A73. A slight modification of the recipe is recommended, by improving the filler content by 0.5% to ensure better compaction.

4 Construction and evaluation of FIBRA test sections

4.1 Test sections in The Netherlands (BAM)

4.1.1 Mixture production and transportation

The FIBRA mixtures for A73 test sections were produced in the BAM asphalt plan BAC in Helmond. An overview of the production process is shown in

Table 15, the temperature registration in the drying drum and the produced mixture are presented in Figure 5 and an the production parameters are included in Table 16. From this information, the following is observed:

- The production temperature of the drying drum is about 30-40ºC higher than that of the mixture temperature.
- The production temperature of mixture FIBRA 1 is approximately 20ºC higher than that of the mixtures comprising pen bitumen.
- The variation in temperature does not differ significantly between mixtures.
- Due to the manual addition of fibres, the production speed of FIBRA 3 and 4 is about 130 ton/hour, slightly lower than the automatically produced FIBRA 1 and 2 (around 145 ton/hour).

Table 15. Production process of reference and experimental mixtures at the asphalt plant

	FIBRA 1	FIBRA 2	FIBRA 3	FIBRA 4
	2L- PA 8 PMB	2L-PA 8 Pen	2L-PA 8 Panacea	2L-PA 8 Aramid
Temperature of aggregates	224°C	192°C	196°C	204°C
Temperature bitumen	180°C	155°C	155°C	155°C
Temperature during mixing	181°C	160°C	159°C	165°C
Order of addition of the different materials	1. aggregates 2. filler 3. bitumen	1. aggregates 2. cellulose fibre 3. filler 4. bitumen	1. aggregates 2. panacea fibre+cellulose fibre 3. filler 4. bitumen	1. aggregates 2. aramid fibre+cellulose fibre 3. filler 4. bitumen
Addition of the fibre (procedure, equipment)		Cellulose fibre was added automatically by blowing	Cellulose fibre was added automatically by blowing Panacea fibre was added manually using low-melt bag in the mixer	Cellulose fibre was added automatically by blowing Aramid fibre was added manually using low-melt bag in the mixer
Mixing times after the addition of the different material	after adding all materials mixing for 25 seconds	after adding all materials mixing for 30 seconds	after adding all materials mixing for 30 seconds	after adding all materials mixing for 30 seconds

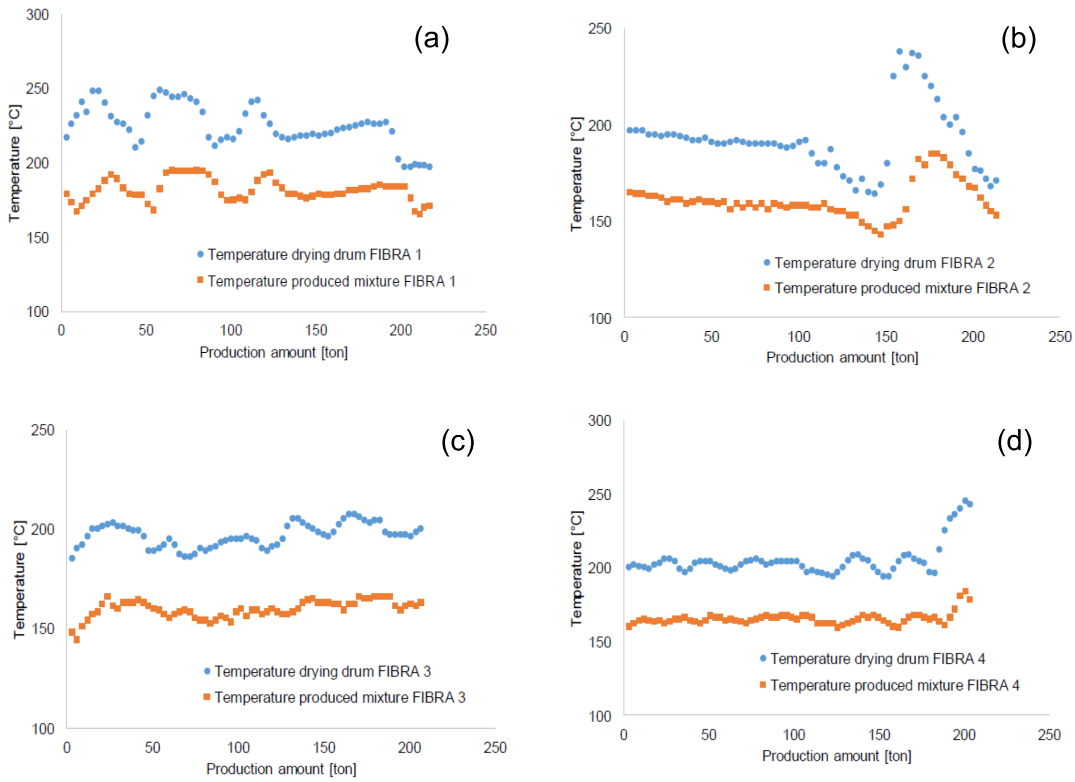

Figure 5. Temperature registration of four FIBRA mixtures: (a) FIBRA 1, (b) FIBRA 2, (c) FIBRA 3 and (d) FIBRA 4.

Table 16. Overview of production parameters

	FIBRA 1	FIBRA 2	FIBRA 3	FIBRA 4
Temperature drying drum [°C]	224,6	192,0	196,5	205,4
standard deviation drying drum [°C]	14,1	17,5	5,7	11,7
Temperature produced mixture [°C]	181,2	160,6	159,5	165,5
standard deviation mixture [°C]	7,7	9,4	4,5	5,3
Total production amount [ton]	217	214	206	201
Total production time [hour]	1,50	1,43	1,58	1,57
Production speed [ton/hour]	145	149	130	128

The transportation is carried out using special isolated trucks for transporting asphalt. The transport distance is about 60km between asphalt plan BAC and project location A73 and took almost 1 hour for the trucks to reach the jobsite.

4.1.2 Laying and compaction

The test sections in the A73 motorway are located near the city of Roermond. Table 17 gives details of the realized sections and their location. Four types of FIBRA 2L-PA 8 mixtures were constructed with a thickness of 25 mm on top of 45 mm of standard 2L-PA 16. To prevent the introduction of unwanted surfacing damage the transition from one mixture to the next was done on the go by simply feeding the next mix to the paving machine whilst finishing the previous section without stopping the installation process. As a results test sections are not separated by a straight manmade joint. Instead, a transition zone of approximately 20-30 meter long (15 m before and 15 m after) may be expected between sections.

Table 17. Location of built test sections in A73

Section	Section code	Location	Length	Under layer	Top layer
1	FIBRA 1/ref	A73 HRL 23.600-23.270	330 m	OL Ref	FIBRA 1/ref
2	FIBRA 2	A73 HRL 23.270-22.920	350 m	OL Ref	FIBRA 2
3	FIBRA 3	A73 HRL 22.920-22.570	350 m	OL Ref	FIBRA 3
4	FIBRA 4	A73 HRL 22.570-22.250	320 m	OL Ref	FIBRA 4

An Infrared line scanner was used to monitor the temperature distribution during laying. The Infrared line scanner was located on the paver to record the surface temperature of the mixture 2 m behind the screed. The counterplots were re-constructed using data from two pavers (this temperature counterplots are available in annex 1, page 37). Table 18 gives the statistics of the temperature distributions obtained from the line scanner. In order to avoid the influence of the transition zone and start-stop, the statistical analysis was carried out with section length without the data of 30 m at the beginning and the end of the section.

- The installation temperature of the FIBRA mixtures with pen bitumen (FIBRA 2, 3 and 4) is 10-20°C lower than that of the FIBRA reference with PMB (FIBRA 1).
- No temperature difference between FIBRA 2, 3 and 4 can be observed.

Table 18. Statistics of paving temperatures of FIBRA mixtures obtained from Infrared line scan data

Section	Analyse	Paver 1	Paver 2
FIBRA 1	Average Temperature	156.20 °C	156.88 °C
	Standard deviation	8.98 °C	11.12 °C
FIBRA 2	Average Temperature	145.02 °C	135.89 °C
	Standard deviation	11.32 °C	8.14 °C
FIBRA 3	Average Temperature	144.43 °C	139.60 °C
	Standard deviation	8.00 °C	8.32 °C

FIBRA 4	Average Temperature	149.25 °C	146.32 °C
	Standard deviation	10.08 °C	6.72 °C

Compaction of all sections was carried out using the same equipment and followed the same standard compaction procedure for all 2L-PA 8 mixtures. No difference between compaction behaviour was observed.

All mixtures are homogenous without clusters of fibres (see Figure 6). The FIBRA mixtures are easier to handle by handwork than the reference mixture with PmB.

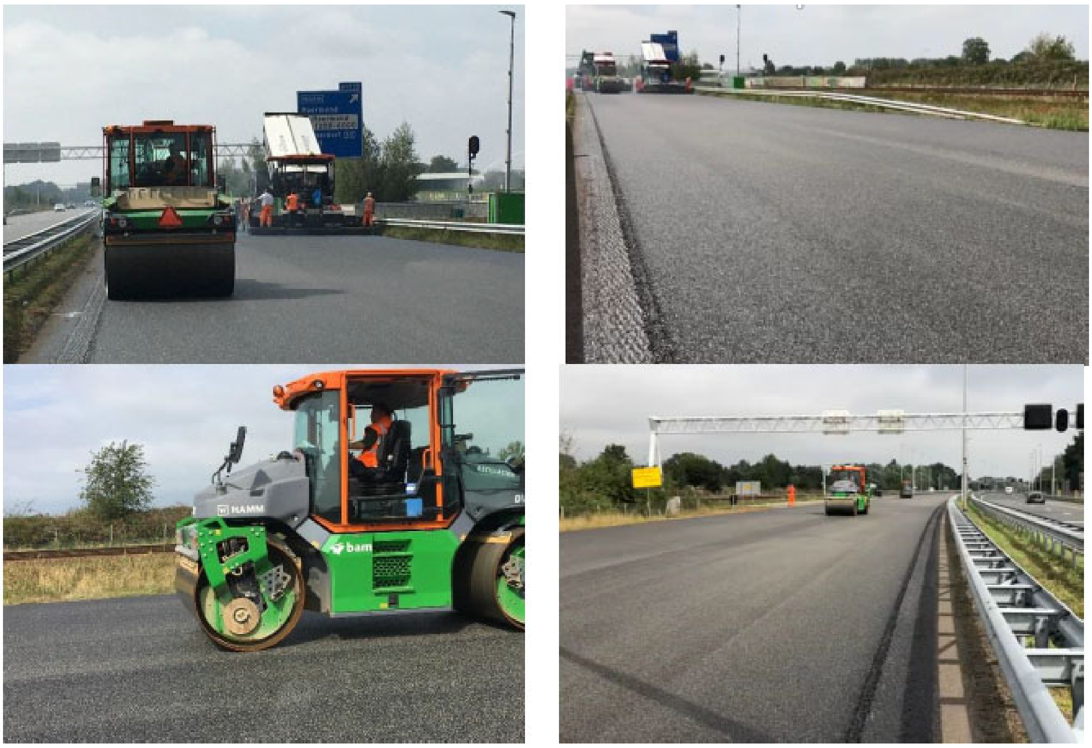

Figure 6. Laying and compaction process of FIBRA mixtures

4.1.3 Laboratory and field evaluation of test sections

MIXTURE COMPOSITION

The mixture composition of the four mixtures at the plant, directly after production and, just before installation, in the hopper of the paver are shown in Table 19 and Table 20 respectively.

Table 19. Production control of the FIBRA mixtures at the plant

Sieve passing	FIBRA 1	FIBRA 2	FIBRA 3	FIBRA 4	Type Test	Minimum (FPC)	Maximum (FPC)
11.2 mm [%]	99.9	99.9	100.0	100.0	100.0		
8 mm [%]	90.8	91.2	91.6	91.0	89.3	81.3	94.3

5.6 mm [%]	36.5	38.7	38.9	35.3	41.6	34.6	48.6
4 mm [%]	15.7	16.8	16.0	17.5	17.1		
2 mm [%]	7.8	9.3	8.7	8.5	8.5	2.5	14.5
0.5 mm [%]	6.7	8.3	7.5	7.3	6.5		
0.063 mm [%]	6.1	7.6	6.8	6.9	6.0	4.0	8.0
Bitumen content [%]	4.87	5.05	5.00	5.05	5.3	4.8	5.8
Mixture temperature [°C]	189	162	163	170			
Density Marshall compaction [kg/m^3]	1902	1945	1936	1957			
Air voids Marshall compaction [%]	24.0	22.2	22.6	21.7	23.0		
Density Gyrator compaction [Kg/m^3]	1826	1860	1835	1850			
Air voids gyrator compaction [%]	27.0	25.6	26.6	26.0			

Table 20. Composition control of the FIBRA mixtures in the hopper

Sieve passing	FIBRA 1	FIBRA 2	FIBRA 3	FIBRA 4	Type Test	Minimum	Maximum
11.2 mm [%]	100.0	99.8	100.0	100.0	100.0		
8 mm [%]	89.4	90.1	90.7	87.8	89.3		
5.6 mm [%]	31.4	37.4	32.9	40.8	41.6		
2 mm [%]	7.2	9.2	8.4	8.6	8.5	3.1	13.9
0.063 mm [%]	5.93	7.47	7.0	7.0	6.0	3.7	8.3
Bitumen content [%]	4,57	4.93	4.87	5.00	5.3	4.7	5.9

From the quality control measurements, the following can be observed:

- There is hardly any difference in gradation and bitumen content between mixtures.
- The production temperature of FIBRA 1 mixture is about 20-30°C higher than that of the FIBRA 2-4.

- The Marshall and gyrator compaction results show that the FIBRA mixtures made with pen bitumen is slightly easier to compact than the FIBRA 1 mixture with PMB. The influence of fibres in FIBRA 3 and 4 on compaction is not significant.
- The results of hopper materials are almost identical than that of the production. This means that the mixture is homogenous and no segregation or draining down of the binder is observed.

DSR MORTAR RESPONSE TEST

Porous asphalt, PA, is one of the typical asphalt mixtures with a stone skeleton. This type of mixture can be seen as a system of coarse aggregates bonded with mortar bridges (mix of sand, filler and bitumen). Generally speaking PA encounters three types of mechanical loading during service,

- Load type 1: Load through passing wheels. This introduces both compression and shear stresses onto individual stones at the PA surface. In order to withstand this load, PA has to be strong enough.
- Load type 2: Passing vehicles deform the pavement construction: deflection. PA thus has to be flexible enough to deform with pavement deflection without problem.
- Load type 3: PA wants to shrink when temperatures drop, e.g. during the decline of temperature at the end of the day. However, the length of the road does not change, implying that surrounding material prevents this desired shrinkage by imposing equal but opposite deformation. PA must be able to absorb this imposed deformation without the buildup of stresses. This again demands that PA is flexible.

Combined the three phenomenon result in raveling damage that may follow from early damage due to a lack of strength (type 1) and damage after long term service, raveling, due to lack of flexibility after aging (type 2 and type 3). In the Netherlands, raveling after long term of service is the predominant type of damage for Porous Asphalt, PA, and terminates the lifespan of PA. The flexibility of PA is very much dependent on the flexibility of its mortar. As a result, the raveling susceptibility of PA may be evaluated by determination and interpretation of the flexibility of its mortar.

In this research, a DSR mortar test was conducted to evaluate the flexibility of the mortar with the procedure developed during the LOT program [Huurman et al. 2010] as shown in Figure 7. For the production of test specimens mortar is retrieved from the mixtures with a hot spatula. The mortar is then made into a 20 mm high column having a 6 mm in diameter. During the DSR testing, these columns were subjected to sinusoidal loading at pre-set frequency and temperature. The mortar response to this mechanical loading was measured at a range of frequencies and temperatures. Through the combined data master curves of stiffness, G*, and phase lag, δ, were fitted at a reference temperature of -10°C.

Figure 7. DSR mortar response test of hopper materials on A73 test sections

The FIBRA mixtures to be evaluated were obtained from the hopper for the quality in the virgin state. A laboratory accelerated aging process was also conducted on the FIBRA mixtures for evaluating the flexibility after aging according to the procedure of Jemere [Jemere Y. 2010]. In this procedure 5 cm thick layer of uncompacted loose FIBRA mixture is aged in an oven for 44 hours at 135°C. It is expected that the aging hardening that is obtained in this manner is equivalent to 10 years of aging of porous surfacing PA 16 in the Netherlands [Jemere Y. 2010].

For making a good comparison of the performance of the mortar in different FIBRA mixtures, a comparison of the bitumen performance is first presented, see Figure 8. Figure 8 gives the results of bitumen mastercurves of both 70/100 pen bitumen and Styrelf 65/105-80 A AP bitumen at a reference temperature of -10°C which were obtained from the database of BAM. Please note that the figures hereafter present fitted models through measured data. The combination of fitted models with original data can be found in Annex 1.

- At high frequency/low temperature range, the complex modulus of the 70/100 pen bitumen is slightly higher than that of the Styrelf bitumen.

- At low frequency/high temperature range, the complex modulus of the Styrelf bitumen is higher than that of the 70/100 pen bitumen due to the working of the polymer.

- The phase angle of 70/100 bitumen ranges from around 15-90° in the whole range. The range of the Styrelf bitumen is 20-60°, clearly indicating the presence of the SBS polymer, especially at low frequency range.

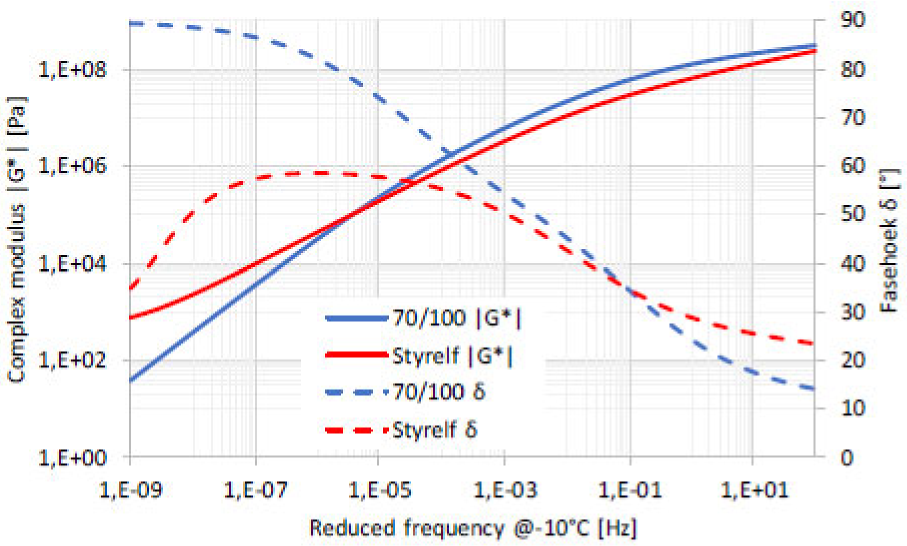

Figure 8. Comparison of the mastercurves of 70/100 PEN bitumen and Styrelf 65/105-80 A AP

Figure 9 present the mastercurves of the 4 FIBRA mixtures in the hopper and after laboratory long-term aging LTA. The following can be observed:

- The mortar of FIBRA 1 mixture obtained from the hopper has lowest complex modulus and a high phase angle due to the presence of the polymer than that of the other three mortars. The mortar of FIBRA 2 mixture has a higher complex modulus and a similar phase angle than that of the mortar from FIBRA 1 mixture. These observations in mortar corresponds also to the observations of bitumen as discussed above in Figure 18.
- The response of the mortar of the mixtures containing fibres FIBRA 3 and 4 are

almost similar to each other. The complex modulus of both mortars are higher than that of the mortar from FIBRA 2 as a result of the fibre reinforcement. The phase angle of both mortars are lower than that of the mortar from FIBRA 2.

- After aging, the response of the mortars with 70/100 pen bitumen are almost the same. The influence of the fibre reinforcement is not significant. The complex modulus of the mortar with Styrelf bitumen is still lower than that of the other mortars. The phase angle of the mortar with Styrelf bitumen is higher than that of the mortars with 70/100 pen bitumen.

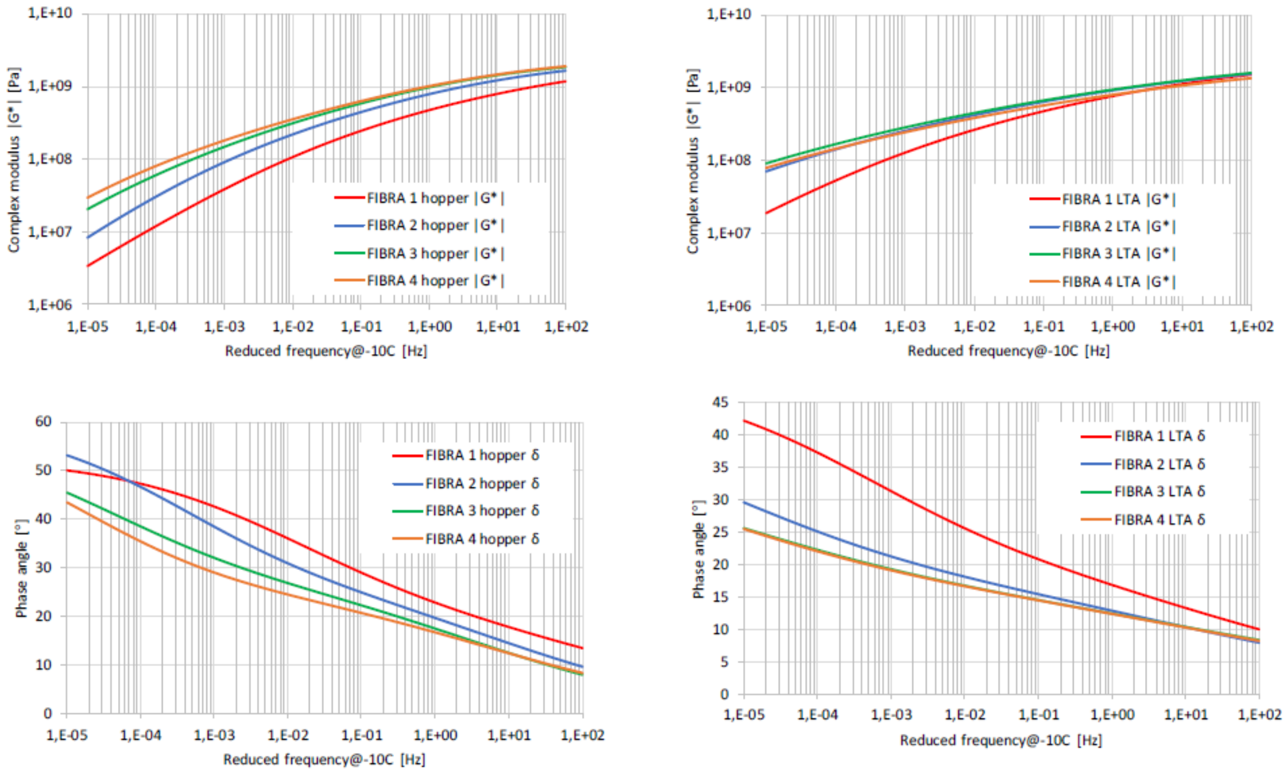

Figure 9. Comparison of the mastercurves of four FIBRA mixtures obtained from hopper (a) and after long-term aging (b)

Figure 10 presents the aging index of the four FIBRA mixtures. The aging index is calculated as the ratio of the complex modulus of the long term aged mortar and that of the mortar from the hopper. The following can be observed,

- The long-term laboratory aging increases the complex modulus of all four mixtures. As indication, the complex modulus at around 1E-5 Hz, the frequency close to the day-night cycle, increases to 2.7 to 8.2 times for different materials.
- The FIBRA 2 mortar experiences the larges increasing of the complex modulus at low frequency range.
- The increase of the complex modulus at low frequency of FIBRA 1 mortar is smaller than that of FIBRA 2 mortar. However, the aging susceptibility of the FIBRA 1 mortar at high frequency range is the highest of all mortars.
- The fibre reinforced FIBRA 3 and 4 mortar show the lowest aging susceptibility of the four tested types of mortar. It seems the presence of the fibre retards ingression of the oxygen into porous asphalt mixtures during the aging process. However, more research is needed to verify this explanation.

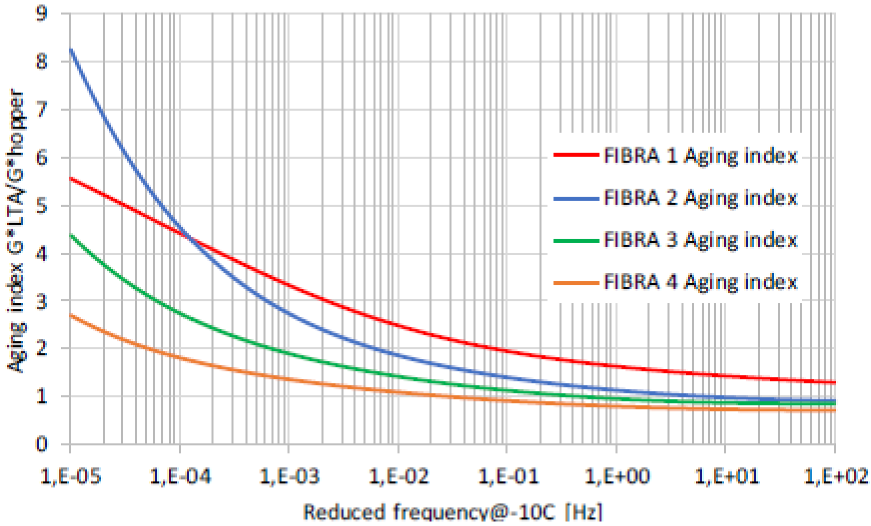

Figure 10. Comparison of aging index of 4 FIBRA mixtures

WATER DRAINABILITY

The evaluation of the water drainability was carried out on the sections before opening to traffic by the use of Becker Test. The Dutch requirement for drainability of 2-layer PA expressed in the Becker outflow-time is maximum 17 second on average and 20 second individual. It can be seen from the results (Figure 11) that all the mixtures have similar water Becker outflow times of 11-14 seconds, all FIBRA mixtures fulfil the requirement.

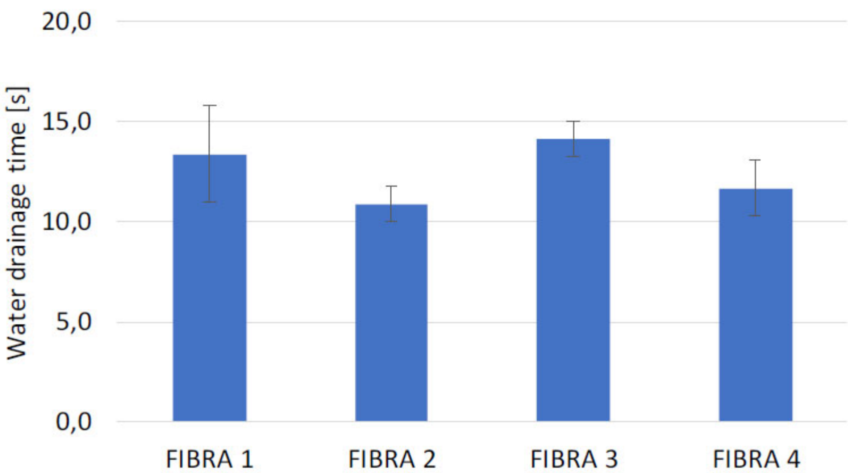

Figure 11. Illustration of water drainability test (Becker Test, left) and the results of Becker test of A73 test sections before opening to traffic (right).

LONGITUDINAL EVENNESS

The longitudinal evenness of the installed FIBRA sections was evaluated by measuring the longitudinal profile according to Dutch standard RAW 2015/71. Based on the results, the parameters f5 and C5 are determined. f5 is the number of bumps and depressions deeper or higher than 5 mm per section of 100 m. C5 is the percentage of the road surface that should be considered as a bump or depression per section of 100 m. For a new road surface the demand is that C5<2%. The measurement of this research was carried out by a third party, Kiwa KOAC, by the use of a High Speed Road Profiler (Q). The measured profile was then evaluated by the use of the parameters f5 and C5 as mentioned above. Table 21 gives the results of the longitudinal evenness of all the sections after three weeks of trafficking. The results indicate that all the sections have a smooth longitudinal profile without unevenness.

Table 21. Results of longitudingal evenness evaluations on A73 sections

		# of sections	# sections with f5>0	Maximum C5	Requirement C5
FIBRA 1	2L- PA 8 PMB	0	0	0	<2%
FIBRA 2	2L- PA 8 Pen	0	0	0	<2%
FIBRA 3	2L- PA 8 Panacea	0	0	0	<2%
FIBRA 4	2L- PA 8 aramid	0	0	0	<2%

SKID RESISTANCE

The skid resistance was measured in the longitudinal direction with a slip ratio of 86% and with a standardized non-profiled PIARC test tyre according to Dutch standard RAW 2015/72. Measurements were carried out with at 70km/hour and repeated up to 3 weeks after opening to traffic. The goal of this short monitoring program is to evaluate the initial development of the skid resistance of the FIBRA sections. In addition week 0 and week 3 the skid resistance measured by the side way force measurement was also carried out.

Table 22 and Figure 12 present the results of the development of skid resistance performance of the slow lane of the A73 test sections during the first 3 weeks of trafficking. The minimum requirement of the skid resistance for Dutch regulation is 0.42. The week 0 measurement was not conducted for the first 900 meter (km 23.6-22.7) of the A73 test section due to joint-repairing activities carried out at the same time of the measurement.

Obtained results indicate that all test sections fulfil the standard and behave good. During the first 3 weeks of trafficking, FIBRA 2, 3 and 4 experience the phase of declining skid resistance due to loss of sanding sand applied during construction in the first week which followed by a phase of increasing skid resistance performance in the following weeks due to the wear-off of the surface mortar films. Due to the use of polymer modification for the reference mixture, the phase of wear-off of the mortar films lasts longer and is not so much observed during the first 3 weeks.

Table 22. Results of skid resistance measurement of both RAW 2015/72 and side way force

	RAW 2015/72 70 km/hour				SWF 80 km/hour	
Location	2R-L	2R-L	2R-L	2R-L	2R-L	2R-L
Time	Week0	Week1	Week2	Week3	Week0	Week3
FIBRA 1		0.531	0.513	0.517		0.587
Standard deviation FIBRA 1		0.018	0.012	0.006		0.025

FIBRA 2		0.560	0.575	0.560		0.655
Standard deviation FIBRA 2		0.014	0.021	0.028		0.007
FIBRA 3	0.550	0.537	0.537	0.570		0.650
Standard deviation FIBRA 3		0.012	0.015	0.000		0,010
FIBRA 4	0.565	0.530	0.535	0.555	0.905	0.645
Standard deviation FIBRA 4	0.007	0.014	0.007	0,007	0.007	0.007

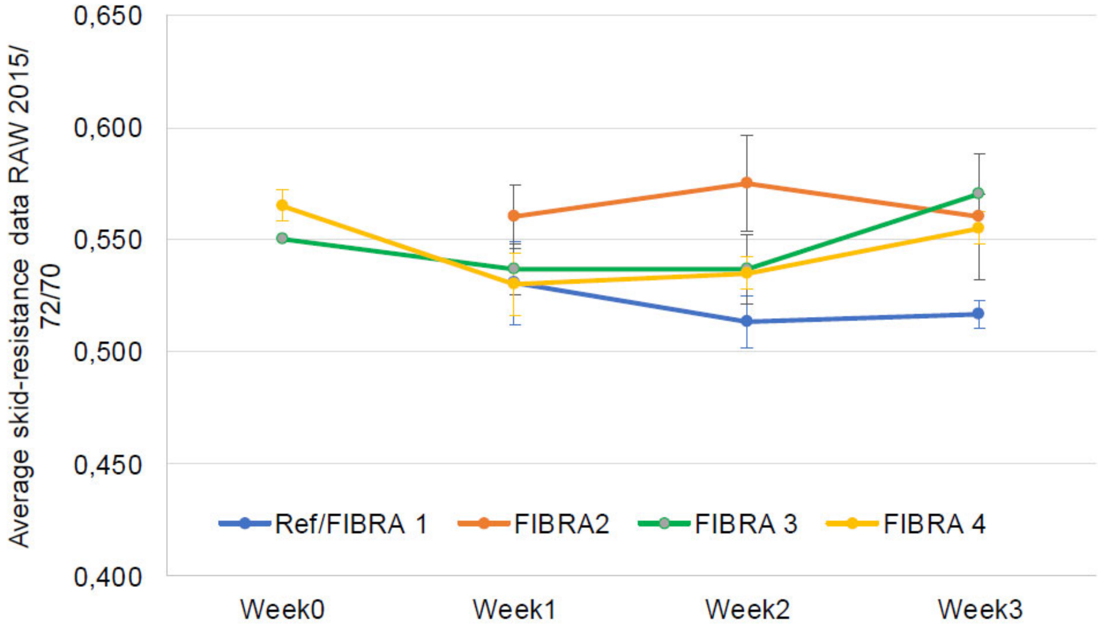

Figure 12. Development of skid resistance performance of slow lane (lane 2) of A73 test sections durign 3 weeks of service.

NOISE MEASUREMENT

12 weeks after construction of the test sections, a noise measurement was carried out using a Close Proximity (CPX) method according to ISO 11819-2. The measurement was carried out with a special designed trailer with microphone (Figure 13). Two different types of tyres were used being standard tyre P1 and H1 according to ISO 11819-3. The P1 tyre is representative for light vehicles (as in de result CPXP) and the H1 tyre is representative for heavy vehicles (as in the result CPXH). Both the slow lane and the fast lane were measured with a speed of 80km/hour.

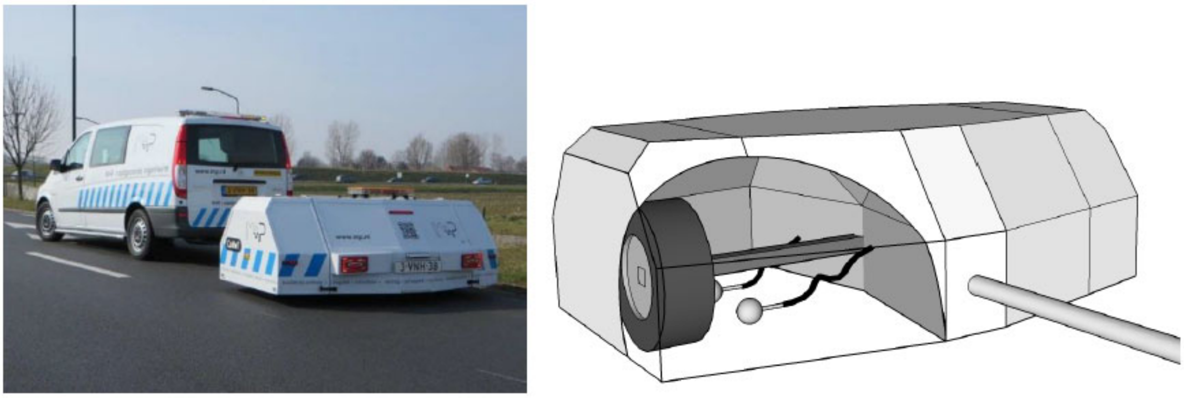

Figure 13. CPX noise measurement.

The results of the noise measurement of FIBRA sections are present in Table 28.

- As shown for light vehicles on average the rolling noise on the right lane is 1.2 dB(A) higher than on the left lane. This can be due to the wearing off of the bitumen film on the right lane due to more intense traffic. For heavy vehicles the difference between two lanes is limited to about 0.5 dB(A).
- The CPXH value for heavy vehicles is slightly 0.2-0.5 dB(A) higher than the CPXP for light vehicles for the left lane. Almost no difference can be found for the right lane.
- The difference between different test sections is neglectable.

Table 23. Results of noise measurement of FIBRA sections by the use of CPX method

Section	Location	CPXP [dB(A)] for light vehicles		CPXH [dB(A)] for heavy vehicles	
		Left lane lane 1	Right lane lane 2	Left lane lane 1	Right lane lane 2
FIBRA 1	23.600-23.270	91.3 (0.5)	92.8 (0.3)	92.5(0.8)	92.5 (0.1)
FIBRA 2	23.270-22.920	91.6 (0.4)	92.9 (0.5)	91.9 (0.1)	92.4 (0.2)
FIBRA 3	22.920-22.570	91.4 (0.4)	92.4 (0.4)	91.9 (0.3)	92.4 (0.2)
FIBRA 4	22.570-22.250	91.3 (0.2)	92.5 (0.3)	91.7 (0.2)	92.3 (0.1)

() standard deviation

VISUAL INSPECTION

A visual inspection of the test section (lane 1, lane 2 and emergency lane) was carried out in week 47 (around 3 months of service) by the use of a HR (High Resolution) video camera, which is able to obtain 360° view. Furthermore, the video information is evaluated by an inspection expert according to Dutch standard “DWW handbook Damage Evaluation and Intervention levels for pavement maintenance”. The result indicate that after 3-month of service the test sections are in good condition and no damage is observed.

MONITORING

The A73 test sections will be in monitored for long-term performance by BAM in collaboration with Rijkswaterstaat. At this moment a year 2 and year 5 HD video inspection is planned. These test sections will also be part of the yearly monitoring program of Rijkswaterstaat of visual inspection and skid resistance.

4.1.4 Summary construction and evaluation of test sections

The following can be summarised from the construction and evaluation of the FIBRA test sections in the A73,

- For the production of the fibre reinforced PA, the fibres were pre-packed in melt bags and fed into the mixer manually. As a result, the production speed was decreased slightly to 130 ton/hour when compared to that of the automatic process of reference mixture of 150 ton/hour. Similar temperature homogeneity of all mixtures can be observed.
- The installation temperature of fibre reinforced porous asphalt is 20 °C lower than that of the PMB reference section. No difference is observed in the compaction process. No fibre clusters or other production or installation problems occurred.
- Laboratory results show that all FIBRA mixtures have very limited variation in composition both directly after production at the mill and just in advance of installation in the paver hopper.
- The DSR mortar response test show that the PMB mixture is the most flexible mixture before and after aging. The addition of fibre increases the complex modulus and decrease the phase angle of the mortar. The mixture with fibre reinforcement shows less aging susceptibility than that of the reference mixture without fibre and also the PMB mixture with limited increasing of complex modulus after ageing.
- The filed evaluation shows that all FIBRA sections have good performance. All FIBRA sections have identical water drainage performance and longitudinal evenness. The fibre reinforced PA sections have better skid resistance performance than that of the reference section with polymer during the first 3 weeks after opening to traffic. The wearing off of the bitumen film is faster than that of the polymer modified section.
- The noise measurement by the use of a CPX method after 3-month of service indicate that all the sections have similar noise-reducing performance. In general, the right lane generates more rolling noise than the left lane.
- Visual inspection results indicate that after 3months of service, the test sections are in good condition and no damage is observed.
- The test long-term performance of the FIBRA test sections will be monitored by BAM in close collaboration with Rijkswaterstaat. At this moment a year 2 and year 5 HD video inspection is planned. These test sections will also be part of the yearly monitoring program of Rijkswaterstaat of visual inspection and skid resistance.

4.2 Test sections in Norway (VEIDEKKE)

VEIDEKKE and Statens Vegvesen agreed in the implementation of the following asphalt layers in the test sections built in Norway:

- AC11, binder 70/100, reference

- AC11, binder 70/100, PAN fibre
- AC11, binder PMB

The tests sections were paved in June 2020. The mixture composition of the three mixtures are shown in Table 24.

Table 24. Composition of mixtures in the test section

Composition	AC11, binder 70/100, reference (1 KG)	AC11, binder 70/100, PAN (1KG)	AC11, binder PMB (1KG)
PEN Bitumen (kg)	0.056		0.055
PMB Bitumen (kg)		0.056	
Aggregate fraction (kg)	0.865	0.865	0.851
Filler (kg)	0.078	0.0775	0.077
Cellulose Fibre (kg)			
Fibre (Kg)		0.0015	

4.2.1 Mixture production

The FIBRA mixtures for the test section were produced in Veidekke's asphalt plant close to Trondheiim. An overview of the production process is shown in Table 25.

Table 25. Production process of reference and experiemental mixtures at the asphalt plant

	AC11, binder 70/100, reference (1 KG)	AC11, binder 70/100, PAN (1KG)	AC11, binder PMB (1KG)
Temperature of aggregates	160	160	175
Temperature bitumen	160	160	175
Temperature during mixing	160	160	175
Order of addition of the different materials	1. Aggregates 2. Filler 3. Bitumen	1. Aggregates 2. Fibre 3. Filler 4. Bitumen	1. Aggregates 2. Filler 3. Bitumen
Addition of the fibre (procedure, equipment)		The fiber is manually feeded into the mixer in bags	
Mixing times after the addition of the different material	21.5	28	21.5

The transportation was carried out using trucks. The transport distance was about 70 km between asphalt plan and project location and took almost 1 hour for the trucks to reach the jobsite.

4.2.2 Laying and compaction

The test sections are located Singsås (Fv 30). Three types of FIBRA AC11 mixtures were constructed with a thickness of 40 mm. The same compaction energy was used (3-4 passes) and the measured mean void content of each mixture is shown in Table 26. No significant differences were observed between the three mixtures.

Table 26. Mean void content of the three mixtures in the test section

	AC11, binder 70/100, reference (1 KG)	AC11, binder 70/100, PAN (1KG)	AC11, binder PMB (1KG)
Mean void content (%)	3,1	3,4	2,9

The three mixtures looked dense, homogeneous, without clusters of fibres (Figure 14). No visible differences were found between the mixtures.

Figure 14. Illustration of compaction process of FIBRA mixtures.

4.2.3 Laboratory and field evaluation of test sections

WHEEL TRACKING TEST

The plastic deformation of the FIBRA mixtures produced at the asphalt plant was evaluated through a wheel tracking test according to the standard NS-EN 12697-22 (small size device). The obtained results are shown in Table 27. In relation to requirements in Norwegian guidelines, the following can be summarized:

- The AC11 mixture with 70/100 penetration grade bitumen used as referenced does not satisfy any requirements for resistance to permanent deformation.

- The AC 11 mixture with PMB satisfies the requirements for resistance to permanent deformations on roads with AADT > 10000.
- The fiber-reinforced AC 11 mixture with 70/100 penetration grade bitumen satisfies requirements for resistance to permanent deformations on roads with AADT between 5000 and 10000.

Table 27. Wheel tracking test results of the FIBRA mixtures

Type of mixture	WTS_{air}	PRD_{air} (mm)	PRD_{air} (%)
AC11 70/100 ref.	0.173	4.6	9.1
AC11 70/100 + fiber	0.062	2.8	5.5
AC11PMB	0.064	2.3	4.5

WATER SENSITIVITY

The water sensitivity of the FIBRA mixtures produced at the asphalt plant was determined according to the standard NS-ES 12697-12 method A (ITRS). The obtained results are shown in Table 28. All mixtures obtained very good results and largely satisfy the requirements for ITSR value > 80%.

Table 28. ITSR test results of the FIBRA mixtures

Type of mixture	ITSR (%)
AC11 70/100 ref.	99.5
AC11 70/100 + fiber	97.2
AC11 PMB	98.7

ABRASION BY STUDDED TYRES (PRALL)

The abrasion by studded tires (Prall test) of the FIBRA mixtures produced at the asphalt plant was determined according to the standard NS-ES 12697-16. The obtained results are shown in Table 29. The AC11 mixture with PMB and the fiber-reinforced AC 11 mixture satisfy the requirement for AADT between 5001 and 10000. However, the AC11 mixture with 70/100 penetration grade bitumen used as reference only satisfies the requirement for AADT between 1501 and 3000.

Table 29. The Prall test results of the FIBRA mixtures

Type of mixture	Density g/cm³	Abrasion value cm³
AC11 70/100 ref.	2.439	28.5
AC11 70/100 + fiber	2.419	24.3
AC11 PMB	2.441	24.5

5 Conclusions and recommendations

5.1 Conclusions from laboratory research

5.1.1 Porous asphalt (BAM)

- Porous asphalt can be reinforced using synthetic fibres (Polyacrylonitrile and aramid).
- The fibres are homogenously distributed in the mix for laboratory produced mixtures. No clusters of fibres can be found. Aramid fibres with different lengths have no influence on the homogeneity of the mixture.
- The use of synthetic fibres does not prevent binder drainage due to limited percentage of added fibre, especially when a fibre blend is used such as aramid/polyolefin blends. Instead, a combination of synthetic fibres and cellulose fibres is used to prevent mortar drainage in bitumen-rich mixtures such as 2L-PA 8 which is used in this trial.
- The use of synthetic fibres in combination of a pen grade bitumen for 2L-PA 8 allowed to reduce the production temperature by approximately 20°C compared to that of the reference mixture produced with polymer modified bitumen. Given the difference in production temperature, no differences in laboratory production and compaction were observed. This implies that differences in bitumen properties are compensated with the difference in production temperature.
- The mechanical strength of fibre reinforced PA is similar to that of PA produced with a pen grade bitumen. The water sensitivity of the fibre reinforced PA is slightly lower than that of the pen grade bitumen mixtures.

5.1.2 Asphalt concrete (VEIDEKKE)

- Asphalt concrete can be reinforced using PAN fibres.
- The fibres are homogeneously distributed in the mixture. No clusters of fibres are found.
- The Marshal values of the AC mixes with and without fibres are about the same level, or slightly better, for AC mixes containing fiber compared with the mixes without fiber.
- The deformation properties evaluated using wheel tracking test are better for AC mixes with fiber compared to the mixes with 70/100 penetration grade bitumen. Mixes with PMB gave the best results for both Marshall and wheel tracking tests.

5.2 Conclusions from plant trials (BAM)

- The FIBRA 4 mixture with aramid fibre can well be produced in an existing production plant. Addition of fibres can be carried out manually through the inspection gate of the mixer with a pre-packed low-smelt bag.
- The produced FIBRA 4 mixture was homogenous with limited variation. The production temperature was around 180 °C due to limited production amount. No segregation or binder drainage is observed during production and also after 1 hour transport simulation.

- The mixture in the trial production are slightly more porous than that equivalent laboratory produced mixture.
- The installation of the FIBRA 4 mixture can be carried out with regular equipment and the strategy of standard 2L-PA 8. The workability of the mixture is better than that of the standard 2L-PA 8 with polymer modification.
- The constructed test sections at the plant yard have good water drainability and good layer thickness.

5.3 Conclusions from field trials

5.3.1 Porous asphalt (BAM)

- For the production of the fibre reinforced PA the fibres were pre weighed and pre packed in melt bags and fed into the mixer manually. As a result, the production speed slightly decreased to 130 ton/hour compared to that of the automatic process of reference mixture of 150 ton/hour. Similar temperature homogeneity of all mixtures can be observed.
- The installation temperature of fibre reinforced porous asphalt is 20 °C lower than that of the PMB reference section. No difference is observed on the compaction process. No fibre clusters or other production or installation problems occurred.
- Laboratory results show that all FIBRA mixtures have very limited variation in composition both directly after production at the plant and just in advance of installation in the paver hopper.
- The DSR mortar response test show that the PMB mixture is the most flexible mixture before and after aging. The addition of fibre increases the complex modulus and decrease the phase angle of the mortar. The mixture with fibre reinforcement shows less aging susceptibility than that of the reference mixture without fibre and also the PMB mixture with limited increase of the complex modulus after ageing.
- The filed evaluation shows that all FIBRA sections have good performance. All FIBRA sections have identical water drainage performance, longitudinal evenness. The fibre reinforced PA sections have better skid resistance performance than that of the reference section with polymer during the first 3 weeks after opening to traffic. The wearing off of the bitumen film is faster than that of the polymer modified section.
- The noise measurement by the use of a CPX method after 3 months of service indicate that all the sections have similar noise-reducing performance. Right lane generates in general more noise than the left lane.
- The visual inspection results indicate that after 3 months of service the test sections are in good condition and that no damage is observed.
- The test long-term performance of the FIBRA test sections will be monitored by BAM in close collaboration with Rijkswaterstaat. At this moment a year 2 and year 5 HD video inspection is planned. These test sections will also be part of the yearly monitoring program of Rijkswaterstaat of visual inspection and skid resistance.

5.3.2 Asphalt concrete (VEIDEKKE)

- No problems were identified with the different types of mixes. The only challenge, which is limiting for the use of the fiber, is that it must be fed into the factory manually.
- The fiber reinforcement of the AC11 mixture with penetration grade bitumen (70/100) increases the plastic deformation performance of the mixture. However, it does not achieved the performance of the polymer-modified mixture.
- The fiber reinforcement of the AC11 mixture with penetration grade bitumen improves the performance of the mixture in terms of its resistance to the abrasion by studded tires, satisfying the same requirement as the polymer-modified mixture.

5.4 Recommendations

5.4.1 Porous asphalt (BAM)

- Porous asphalt can be reinforced using synthetic fibres (both Polyacrylonitrile and aramid). Both fibres can be integrated into current mix design and production/installation process of porous asphalt without technical difficulty. The use of fibre reinforcement may positively contribute to mixture performance as indicated by the strength and stiffness of the mortar. It is anticipated that mortar with fibre reinforcement will have better ageing resistance than mortar without reinforcement and also than mortar containing polymer modified bitumen.
- The use of fibre in 2L-PA 8 makes the use of polymer modified bitumen superfluous. An advantage of this is that fibre-reinforced 2L-PA 8 with pen bitumen is produced at a lower temperature than its polymer-modified equivalent (e.g. FIBRA 1, 2L-PA 8 with Styrelf). This lowers energy consumption during production. In addition, the workability of fibre-reinforced 2L-PA 8 is better than that of polymer modified 2L-PA 8.
- A further optimization of fibre type, aspect ratio (length/diameter) and dosage is recommended in terms of mechanical performance, ageing resistance, ravelling resistance and weathering resistance. The used polyacrylonitrile and aramid in FIBRA 3 and 4 in terms of type (e.g. length) and application rate follow recommendation of the fibre producers. A comprehensive understanding in this aspect is important for further application of fibre reinforcement.
- Long term monitoring of the constructed test section and the formation of a portfolio of test sections by constructing more new sections is recommended. It is believed that that the presence of the fibre retards ingression of the oxygen into porous asphalt mixtures during the aging process. This will delay the process of mortar aging so lengthening the OPA service life. This hypothesis can only be verified through field monitoring followed by analysis of field data of fibre reinforced porous asphalt. This underlines the importance of the suggested portfolio.
- The development of an automatic dosage system for fibre application is recommended. Such a system will contribute to worker safety and production efficiency.

5.4.2 Asphalt Concrete (VEIDEKKE)

- The fiber reinforcement of the AC11 mixture increases the plastic deformation performance of the mixture. However, it does not achieved the performance of the polymer-modified mixture. The fiber reinforcement of the AC11 mixture with penetration grade bitumen improves the performance of the mixture in terms of its resistance to the abrasion by studded tires, satisfying the same requirement as the polymer-modified mixture.

- Low temperature properties, which is an important parameter in the Norwegian climate, should be analysed further.
- The test sections should be followed up to gain experience with the long-term properties.
- If mixes with fiber are produced, it is recommended to develop an automatic dosage system for fibre application. An automatic system is necessary for the working environment.

6 References

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Annexes

- Report 2L-PA combined trial sections A73 HRL 23.600-21.600