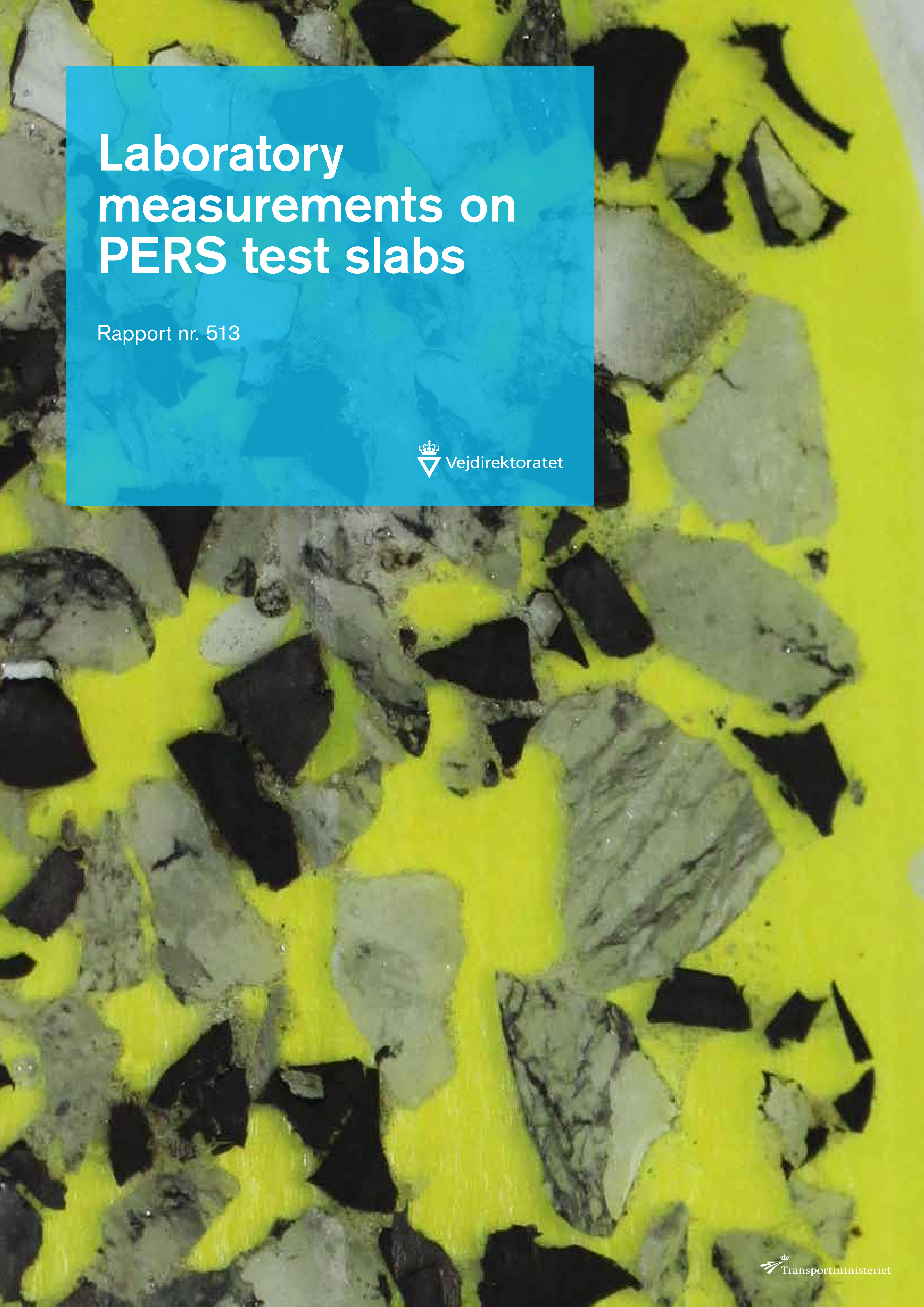

Laboratory measurements on PERS test slabs

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Laboratory measurements on PERS test slabs

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PoroElastic Road SUrface: an innovation to Avoid Damages to the Environment

Contents

Preface

The PERSUADE project aims at developing the experimental concept of poroelastic road surfacing (PERS) into a feasible noise-abatement measure as an alternative to, for example, noise barriers. It is expected that PERS may provide substantially higher noise reductions than the best of conventional paving materials. The specific feature of this new type of road surfacing is that it includes a substantial proportion of rubber granules from recycled car tyres bound with a synthetic resin, such as polyurethane.

PERSUADE is the acronym for PoroElastic Road SUrface: an innovation to Avoid Damage to the Environment. The project programme comprises an extensive investigation in the laboratory to develop a durable mixture, the construction of seven test sections in five partner countries, a monitoring effort for the test sections (noise, rolling resistance, skid resistance, durability, winter behaviour, etc.), and a study of all conceivable environmental and economic aspects. The project has been scheduled for a duration of six years. Twelve partners from seven European countries are cooperating in this project, including research institutes, universities and companies representing the involved industry sectors:

- Belgian Road Research Centre (BRRC), Project coordinator
- Swedish National Road and Transport Research Institute (VTI)
- Danish Road Directorate (DRD)
- NCC Roads AS (NCC)
- Slovenian National Building and Civil Engineering Institute (ZAG)
- Polish Road and Bridge Research Institute (IBDiM)
- Technical University of Gdansk (TUG)
- Dura Vermeer Infrastructuur NV (DVI)
- European Tyre Recyclers Association (ETRA)
- HET Elastomertechnik GmbH (HET)
- Katholieke Universiteit Leuven (KULeuven)
- The French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR)

See also the PERSUADE website at:
http://persuade.fehrl.org/

This report has been produced within Work Package WP 5 of the project, which deals with "Monitoring of test sections" and is led by the Danish Road Directorate (DRD). This report is about results of laboratory testing of PERS test slabs performed by DRD and IFSTTAR. The report presents the results of measurements performed on five different versions of PERS material from Denmark, Belgium, Slovenia and Sweden in the period October 2011 until November 2013. The report has been produced by researchers from the DRD and IFSTTAR.

The authors would like to thank the enthusiastic DRD, and IFSTTAR staff for their work in performing measurements and analysis. The authors are solely responsible for the contents of this document. The report has been reviewed by Luc Goubert from the Belgian Road Research Institute (BRRC).

This work is financed by the European Commission as well as by the Danish and French partners. The authors are grateful for the financial support for the major part of this project from the European Commission though its 7th Framework Programme.

Forord

PERSUADE projektets formål er at udvikle poroelastiske vejbelægninger (PERS) som en mulig støjreducerende metode alternativt til fx støjskærme. Det forventes, at PERS vil kunne yde en væsentlig højere støjreduktion end de bedste traditionelle støjreducerende vejbelægninger. Den særlige egenskab ved denne nye type vejbelægning er, at den består af traditionelt stenmateriale samt en væsentlig andel gummigranulat fra genanvendte bildæk bundet sammen med polyuretan.

PERSUADE er akronym for "PoroElastic Road SUrface: an innovation to Avoid Damages to the Environment" (Porøse og elastiske slidlag, en ny metode til at undgå skader på miljøet). Projektprogrammet inkluderer omfattende laboratorieundersøgelser for udvikling af en holdbar blanding, konstruktion af syv teststrækninger i fem partnerlande, et måle- og moniterings program for teststrækningerne (støj, rullemodstand, friktion, holdbarhed, egenskaber om vinteren osv.) samt undersøgelse af miljømæssige og økonomiske aspekter. Projektet planlægges gennemført over seks år. Tolv partnere fra syv europæiske lande samarbejder i dette projekt, herunder forskningsinstitutter, universiteter og firmaer, der repræsenterer de involverede industrisektorer. Partnerne er:

- Belgian Road Research Centre (BRRC), Projekt koordinator
- Swedish National Road and Transport Research Institute (VTI)
- Vejdirektoratet i Danmark (DRD)
- NCC Roads A/S (NCC)
- Slovenian National Building and Civil Engineering Institute (ZAG)
- Polish Road and Bridge Research Institute (IBDiM)
- Technical University of Gdansk (TUG)
- Dura Vermeer Infrastructuur NV (DVI)
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- The French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR)

Yderligere oplysninger om PERSUADE findes på hjemmesiden: http://persuade.fehrl.org/

Denne rapport er blevet udarbejdet i projektets arbejdspakke 5, omhandlende målinger og monitering af teststrækninger. Denne arbejdspakke ledes af Vejdirektoratet i Danmark. Rapporten beskriver resultaterne fra målinger udført på fem forskellige versioner af PERS materialet fra Danmark, Belgien, Slovenien og Sverige produceret i perioden oktober 2011 til november 2013. Rapporten er skrevet af forskere fra Vejdirektoratet samt det franske institut IFSTTAR.

Forfatterne vil gerne takke det entusiastiske personale hos Vejdirektoratet og IFSTTAR som har stået for gennemførelsen af målinger og analyser. Forfatterne er kun ansvarlige for rapportens indhold. Rapporten er kvalitetskontrolleret af Luc Goubert fra det belgiske vejforskningsinstitut BRRC.

Dette arbejde er finansieret af EU Kommissionen samt de danske og franske partnere. Forfatterne er taknemmelige for den finansielle støtte til størstedelen af dette projekt fra EU kommissionens 7. rammeprogram.

Summary

Test slabs of five different PERS test material have been produced. The test materials are named Arnakke, Kalvehave, Nova Gorica, Linköping and Sterrebeek. The test slabs are produced of aggregates that are a mix of stone and rubber from scrapped tyres. The composition of the material is in the order of magnitude of 50 % stone aggregates and 50 % rubber aggregates by volume. The binder used for the materials is polyurethane. The Nova Gorica and Linköping slabs have a maximum aggregate size of 3 mm and are produced at a factory. The three others have a maximum aggregate size of 5 mm and are produced at the road side. The test slabs were produced with different materials under different production conditions.

The purpose was to perform laboratory testing of the slabs to investigate how they perform in relation to the requirements and expectations for poroelastic pavements (PERS) developed by the PERSUADE project. The measurement types included are Pendulum friction tests, drainability, acoustical absorption, built in air void, surface texture and mechanical impedance. Thin section analysis was performed using microscopy and visual inspection. For practical reasons it have not been possible to perform all seven types of measurements on all test slabs.

All the measured friction levels using the Pendulum method are at or higher than the old Danish 45 guideline. The Arnakke test slab has the lowest friction of 45. The friction of the two factory produced test slabs with small aggregates of 3 mm (Nova Gorica and Linköping) is the highest but followed closely by the test slabs from Kalvehave and Sterrebeek with larger aggregates of 5 mm.

The image evaluation of the thin and plane sections through the layers from pavement surface to the bottom gives some qualitative indications of the durability of the test slabs:

- The polyurethane used in the Kalvehave mix had a low viscosity and ran off the top aggregates and accumulated in the bottom layers. This might influence the durability of the slabs.

- For the Sterrebeek test slab the polyurethane is evenly distributed down through all layers of the pavement and the polyurethane is coating the stone and rubber aggregates on all sides. Due to this, the strength of the Sterrebeek slab must be considered better than the Kalvehave slab.

- A lot of dust can be observed at all layers of the Nova Gorica test. It seems that the dust attracts the polyurethane and the polyurethane accumulates on the small grains. Therefore the polyurethane coating of the stone and rubber aggregates is not very good. This will presumably reduce the strength of the slab.

- The polyurethane of the Linköping is evenly distributed down through all layers of the pavement. The thickness of the polyurethane film around the aggregates is very thin. The area of the polyurethane binding between the aggregates is quite small. This will presumably reduce the strength of these slabs.

The on-site produced slabs with 5 mm aggregates from Arnakke and and Sterrebeek have very good drainability of 3.2 and 5.0 seconds comparable to new two-layer porous asphalt. The drainability of the Linköping test slab with the small 3 mm aggregates is 22 seconds and less good than the two slabs with 5 mm aggregates but still in a good state with high drainability. This might be caused by the smaller aggregates resulting in smaller dimensions of open communicating voids in the pavement.

Absorption spectrums from Sterrebeek and Arnakke are similar, with a high absorption coefficient of around 0.9 in the 1000 Hz band followed by the spectrum from Linköping with a lower absorption coefficient of 0.72. The spectre from Nova Gorica has a peak value in the 800 Hz band with an absorption coefficient of 0.61. The spectre from Kalvehave has a peak in the 630 Hz band, with the lowest absorption coefficient of 0.48. The design goal was to get the maximum absorption between 600 and 1000 Hz and this goal has been reached for all the test pavements

according to these absorption measurements on cores from the test slabs.

The target air void for the PERS mix has been estimated to be 30 %. Generally the air void is quite high and around the target level for the Kalvehave, Nova Gorica and Linköping test slabs and a less for the Sterrebeek test slab.

The MPD of Arnakke and Sterrebeek test slabs are of the same magnitude of around 0.8 mm, Kalvehave a little lower at 0.67 mm, and Linköping significant lower at 0.31 mm. For the macro texture, the goal has been to get a high texture level at the short wavelengths and a low texture level at the longer wavelengths. This has been achieved for the test slabs.

The mechanical impedance expressed as the dynamic Young modulus (E) in increasing order is 64 MPa for Kalvehave test site, 96 MPa for Arnakke test site, 102 MPa for Linköping samples, 208 MPa for Nova Gorica samples and 526 MPa for Sterrebeek sample. The ratio is about 8 between the softer and the stiffer PERS, while it would be between 30 and 250 if the PERS were compared to a very stiff Dense Asphalt Concrete ($E \cong 15000$ MPa).

The influence of the parameters in relation to getting a road pavement with a low tyre-road noise emission level has been evaluated as the following on the background of the above measurement results. The prefabricated test slabs with 3 mm aggregates from Linköping should have the best performance in relation to low tyre road noise emission together with the on-site produced Arnakke test slabs with 5 mm aggregates. This evaluation can be somewhat biased because it is based on measurements performed on two types of prefabricated test slabs (Nova Gorica and Linköping) that can be considered produced under ideal conditions and three test slabs produced in moulds at the road side not securing optimal production conditions (Arnakke, Kalvehave and Sterrebeek).

Sammenfatning

Prøvepladerne er fremstillet af fem forskellige versioner af PERS materialet. Disse plader benævnes Arnakke, Kalvehave, Nova Gorica, Linköping og Sterrebeek. Pladerne er fremstillet af gummigranulat fra gamle bildæk og stenmateriale. Der er anvendt ca. 50 % gummi granulat og 50 % stenmateriale – angivet som materialernes rumfang. Det anvendte bindemiddel er polyuretan.

Til pladerne fra Nova Gorica og Linköping er der anvendt sten og gummi materiale med en maksimal stenstørrelse på 3 mm og disse plader er fabriksfremstillede. Til de tre andre plader anvendes materiale med en maksimal stenstørrelse på 5 mm og disse plader er fremstillet i vejsiden i forbindelse med udlægning af PERS prøvestrækninger. De fem test plader er således fremstillet af forskellige materialer under forskellige produktionsbetingelser.

Formålet med laboratorietestning af disse plader er at undersøge egenskaberne i relation til de krav og forventninger til PERS materialet der er i PERSUADE projektet. Målingerne omfatter friktion, permeabilitet, akustisk absorption, indbygget hulrum, overflade tekstur, mekanisk impedans samt analyser i mikroskop af tynd- og planslib. På grund af praktiske forhold har det ikke været muligt at foretage alle syv typer målinger på alle prøve pladerne.

På alle PERS pladerne er der med pendul metoden målt friktionsindex som ligger på niveau eller højere end den gamle danske vejledende friktionsindex værdi på 45 for denne metode. Pladen fra Arnakke har den laveste friktion, målt til et 45. De to fabriksfremstillede plader med 3 mm stenstørrelse (Nova Gorica and Linköping) har den bedste friktion tæt fulgt af pladerne fra Kalvehave og Sterrebeek med større stenstørrelse på 5 mm.

Billedanalyse af tynd- og planslib fra belægningsoverfladen og ned til bunden giver nogle kvalitative indikationer om test pladernes holdbarhed:

- Det anvendte polyuretan ved Kalvehave havde en lav viskositet og løb fra stenmaterialet i belægningens top og samlede sig i bunden af belægningen. Dette kan betyde en reduceret holdbarhed.

- På Sterrebeek pladen er polyuretanet jævnt fordelt ned gennem belægningens lag og polyuretanet omhyller sten og gummi materiale på alle sider. Af disse grunde må det forventes, at denne belægning har en bedre holdbarhed end Kalvehave belægningen.

- På pladen fra Nova Gorica ses i alle lag meget fint støv. Det ser ud til at støvet tiltrækker polyuretanet som akkumuleres på de små støvkorn. Derfor er sten og gummi materialet ikke godt omhyllet af polyuretan. Dette vil formodentlig reducere styrken af denne belægning.

- På pladen fra Linköping er polyuretanet jævnt fordelt ned gennem pladens lag. Polyuretan filmen rundt om sten og gummi materiale er meget tynd. Arealet af polyuretan mellem sten og gummi materiale er meget lille, hvilket formodentlig vil reducere styrken af denne belægning.

De vejsideproducerede testplader fra Arnakke og Sterrebeek har en god permeabilitet målt med en gennemløbstid på 3,2 og 5,0 sekunder. Derimod er permeabiliteten for pladen fra Linköping med 3 mm stenstørrelse 22 sekunder, hvilket er en væsentlig forøgelse i forhold til pladerne med 5 mm stenstørrelse om end der stadig er tale om en rimelig permeabilitet. Forklaringen kan være, at det mindre sten og gummi materiale skaber mindre dimensioner for porerne i belægningen.

Absorptionsspektrene fra Sterrebeek og Arnakke er nærmest identiske med den højeste absorptions koefficient på ca. 0,9 ved 1000 Hz efterfulgt af spektret fra Linköping med en mindre absorptions koefficient på ca. 0,7. Spektret fra Nova Gorica har et toppunkt ved 800 Hz med en absorptions koefficient på ca. 0,6. Spektret for Kalvehave har et toppunkt ved 630 Hz og den laveste absorptions koefficient på ca. 0,5. Målet var at designe en belægning med absorptions toppunkt mellem 600 og 1000 Hz og dette mål er opfyldt for alle belægningerne.

Målet for det indbyggede hulrum for PERS belægningerne er 30 %. Generelt er det indbyggede hulrum højt og omkring målsætningen for pladerne fra Kalvehave, Nova Gorica og Linköping mens det ligger lavere for Sterrebeek pladen.

Tekstur målingerne viser, at MPD for Arnakke og Sterrebeek pladerne ligger i samme størrelsesorden omkring 0,8 mm. Kalvehave ligger lidt lavere på 0,67 mm mens Linköping ligger signifikant lavere på 0,31 mm. For makro teksturen var målet at opnå et højt teksturniveau ved de korte bølgelængder og et lavt tekstur niveau ved de længere bølgelængder. Dette er blevet opfyldt for alle testpladerne.

Den mekaniske impedans udtrykt som Youngs modul (E) ligger i stigende orden på 64 MPa for Kalvehave pladen, 96 MPa for Arnakke, 102 MPa for Linköping, 208 MPa for Nova Gorica og 526 MPa for Sterrebeek pladen. Forholdet mellem den blødeste og den mest stive PERS plade er faktor 8, men det vil alligevel ligge 30 til 250 gange lavere sammenlignet med en almindelig tæt asfaltbeton som ligger på 15000 MPa.

Betydningen af de syv forskellige parameter i forhold til at opnå en belægning med et lavt dæk-vejbane støjniveau er blevet vurderet samlet på baggrund af de ovenstående måleresultater. Den præfabrikerede plade med 3 mm stenstørrelse fra Linköping vurderes at have den bedste virkning i relation til et lavt støjniveau sammen med den vejsidefremstillede plade fra Arnakke med 5 mm stenstørrelse. Denne vurdering påvirkes af det forhold, at de to fabriksfremstillede plader (Nova Gorica og Linköping) må betragtes som fremstillet under ideale forhold, hvorimod de tre plader som er fremstillet i forme langs vejsiden (Arnakke, Kalvehave og Sterrebeek) ikke er fremstillet under optimale produktionsforhold.

1. Introduction

Before or at the same time as the construction of smaller or full scale test sections in the PERSUADE project, slabs of the different PERS test material have been produced in the laboratory, at the factory or at the roadside.

The purpose of producing these test slabs was to perform laboratory testing to investigate how they perform in relation to the requirements and expectations for poroelastic pavements developed by the PERSUADE project.

The main purpose of the PERSUADE project is to develop and test a durable PERS pavement with a high noise reduction. It is not possible to perform real noise measurements using either the road side SPB method or the CPX trailer method on the test slabs. Therefore another series of measurements have been performed in the laboratory that can give an indication of the order of magnitude of the noise levels that can be expected at a full scale test section on a road with real traffic. The measurement types included are the following:

- Pendulum friction tests (EN 13036-4) in wet conditions have been used to get an indication of the friction of the PERS materials as it is important that the full scale pavements can be expected to have a good friction over the national limit values (see Chapter 2).
- Drainability measurements were performed as an expression for permeability (see Chapter 3).
- The acoustical absorption was measured using the tube method (see Chapter 4).
- The built in air void was measured using image analysis on plane sections cut form the material (see Chapter 5).
- The surface texture of the pavements was measured using a DRD high resolution laser equipment (see Chapter 6).
- The mechanical impedance was measured with an equipment developed by IFSTTAR as an expression of the elasticity of the PERS materials (see Chapter 7).
- Thin section analysis was performed using microscopy and visual inspection. By this method developed by the DRD it is possible to look down into the surface structure and to perform a visual assessment of thin and plane sections cut from slabs. The physical structure of the pavement material can be performed at the total thickness of the test slab (see Chapter 8).

For practical reasons it have not been possible to perform all seven types of measurements on all test slabs representing the five different PERS materials, see Table 1.2. The slabs used in Slovenia had a limited size and therefore it was not possible to perform all types of measurements on these slabs.

The five PERS test materials included in this investigation are the following:

1. A first small scale PERS test section (1.5 times 7 m) was constructed at the Arnakke test site in Denmark in October 2011. At the same time some test slabs were constructed at the road side in moulds [1, 2]. The compaction was performed with a small steel roller.
2. A first full scale PERS test section on a real road was constructed at Kalvehave in Denmark in August 2013 [8]. At a nearby road depot where the mixing plant was situated some test slabs were constructed in moulds [3]. The compaction was performed with a small steel roller.
3. HET Elastomertechnik in Germany has produced some small PERS slabs in their factory. They have been transported to Slovenia and been glued to some concrete blocks with the shame shape and size. A small scale test track with these blocks (3 times 4 m) has been produced in Nova Gorica in November 2013 in Slovenia.
4. HET Elastomertechnik has also produced some large PERS slabs in their factory. They have been transported to VTI in Linköping where they have been used to construct a small scale test section (1x25 m) in one lane on a road with traffic.
5. A small scale test section has been produced at a parking area in Sterrebeek at the BRRC laboratory in Belgium in November 2013. At the same time some test slabs were constructed at the road side in moulds [4]. The compaction was performed with a small steel roller.

Data from the Arnakke test site in Denmark have already been reported in [2], but they are included here so they can be compared with data from the other 4 test slabs. Some data regarding the five test materials can be found in Table 1.1. Pictures of the test slabs can be seen in Figures 1.1 to 1.5.

Table 1.1:
The PERS test slabs included in this laboratory investigation.

Test Slab	1	2	3	4	5
Location and name	Arnakke	Kalvehave	Nova Gorica	Linköping	Sterrebeek
Producer of material	NCC	NCC	HET	HET	Colas Belgium
Responsible organisation	DRD	DRD	ZAG	VTI	BRRC
Slab dimension's	50X50 cm	50X50 cm	22X11 cm	50X100 cm	54X33 cm
Thickness	30 mm	30 mm	30 mm	32 mm	42 mm
Maximum aggregate size	5 mm	5 mm	3 mm	3 mm	5 mm
Month of production	October 2011	August 2013	September 2013	November 2013	November 2013
Place of production	Outdoor at test site	Outdoor at test site	At factory	At factory	Outdoor at test site in tent

The test slabs are produced of aggregates that are a mix of stone and rubber from scrapped tyres. The composition of the material is in the order of magnitude of 50 % stone aggregates and 50 % rubber aggregates by volume. The binder used for the materials is polyurethane.

When test slabs for Kalvehave were produced the amount of polyurethane binder used was too high. It is the evaluation by the authors that this created a less open and more dense surface texture than intended and different form the surface texture at the full scale Kalvehave test section [3].

Figure 1.1:
The test slab from Arnakke in Denmark.

Figure 1.2:
The test slab from Kalvehave in Denmark. Some parts of the material have been cut away for testing.

Figure 1.3:
The small test blocks produced for the Nova Gorica test track in Slovenia.

Figure 1.4:
The large test slabs produced for the Linköping test track.

Figure 1.5:
The test slab from Sterrebeek in Belgium.

Table 1.2:
Overview of measurements performed on the test slabs.

Test Slab	1	2	3	4	5
Name	Arnakke	Kalvehave	Nova Gorica	Linköping	Sterrebeek
Pendulum friction	X	X	X	X	X
Drainability	X	X		X	X
Acoustical absorption	X	X	X	X	X
Built in air void		X	X	X	X
Surface texture	X	X		X	X
Mechanical impedance	X	X	X	X	X
Thin and plane section analysis	X	X	X	X	X

Because of the small size of the Nova Gorica slab it was not possible to perform all the measurements on this slab in the laboratory (see Table 1.2).

The surface texture on a test slab can be somewhat different than the surface texture of a pavement with the same material mix produced in full scale on a real road. This can be caused by variance in the compaction on the test slabs and the full scale constructions.

The results of the different measurements performed on the five test slabs can be found in the following chapters.

2. Pendulum friction measurements

The friction has been measured with the Pendulum according to EN 13036-4 standard by the laboratory of the Danish Road Directorate on specimens delivered to the laboratory. The test was carried out in wet conditions in the laboratory at a temperature of 21 to 23° C. To perform the test the slider assembly wide and no. 57 has been used. It should be noticed that the results from this test are taken at a small area so the results cannot be directly compared with results from measuring vehicles that are measuring the friction over a long section of the surface. According to an old Danish praxis the friction can be considered acceptable if it is over 45 measured on wet condition with the Pendulum.

The friction has been measured in two directions parallel to two sides of the test slabs called direction A and B in Table 2.1 that shows the results. The average result of direction A and B is also shown in the table. All the measured friction levels are at or higher than the 45 guideline. The Arnakke test slab has the lowest friction of 45. The friction of the two factory produced test slabs with small aggregates of 3 mm (Nova Gorica and Linköping) is the highest but followed closely by the test slabs from Kalvehave and Sterrebeek with larger aggregates of 5 mm. For comparison the friction was also measured at the Arnakke test site on an old dense asphalt concrete and on a new porous asphalt and the results were 70 and 69 [2], a little higher than for the test slabs.

Figure 2.1:
Pendulum friction measurements apparatus.

Table 2.1:
Results from measurement of the friction by Pendulum tester on samples.

Test slab	Temp. [°C]	Measuring direction	Pendulum Test Value	Average result
Arnakke	21	A	44	45
		B	45	
Kalvehave	23	A	55	57
		B	58	
Nova Gorica	22	A	65	64
		B	62	
Linköping	22	A	65	63
		B	61	
Sterrebeek	20	A	60	62
		B	63	

3. Drainability measurements

Figure 3.1:
The drainability was measured using the Becker´s tube equipment.

The drainability of the test slabs has been measured by the Becker's tube method, which is a simple and effective method [5, 7] used by DRD for many years. A transparent tube with a diameter of 140 mm is placed on the road, and the joint between the tube and the road is sealed with putty. A measurement is done by filling the tube with water and registering how long it takes 100 mm of water to drain down into the pavement (see Figure 3.1). The measurements are repeated three times at points close to each other. The result is calculated as the average of the three measurements. The tests have been carried out at temperature from 17 to 22 °C in the laboratory.

The drainability is given as the flow out time in seconds. DRD normally considers a pavement as clogged when the outflow time is more than 75 seconds [6, 7]. If the draining time is less than 30 seconds, the pavement is in a good state with high drainability [5]. For comparison it can be remarked that new two-layer porous asphalt at the Danish test site at Øster Søgade had an outflow time of 3-10 seconds [6].

The results of the drainability measurements can be seen in Table 3.1. The on-site produced slabs with 5 mm aggregates from Arnakke and Sterrebeek have very good drainability of 3.2 and 5.0 seconds comparable to new two-layer porous asphalt. The drainability of the Linköping test slab with the small 3 mm aggregates is 22 seconds and less good than the two slabs with 5 mm aggregates but still in a good state with high drainability. This might be caused by the smaller aggregates resulting in communicating voids in the pavement with smaller dimensions.

The drainability of the slab from Kalvehave with 5 mm aggregates is not as good as the two other slabs with 5 mm aggregates. This might be caused by a too high amount of polyurethane binder used when the Kalvehave slab was produced (see Chapter 1).

Table 3.1:
Results from measuring the drainability by Becker´s tube on samples.

Test Slab	Temperature [°C]	Drainability, outflow time [seconds]
Arnakke	21	5.0
Kalvehave	23	19.0
Nova Gorica	22	Not measured
Linköping	22	22.0
Sterrebeek	20	3.2

4. Acoustical absorption

Figure 4.1:
Impedance tube for measuring acoustical absorption.

Measurements are carried out according to ISO 10534-2 (Acoustics – Determination of sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-function method).

The acoustical absorption measured in an impedance tube, is measured at six cores drilled from test slabs. The impedance tube can be seen at Figure 4.1.

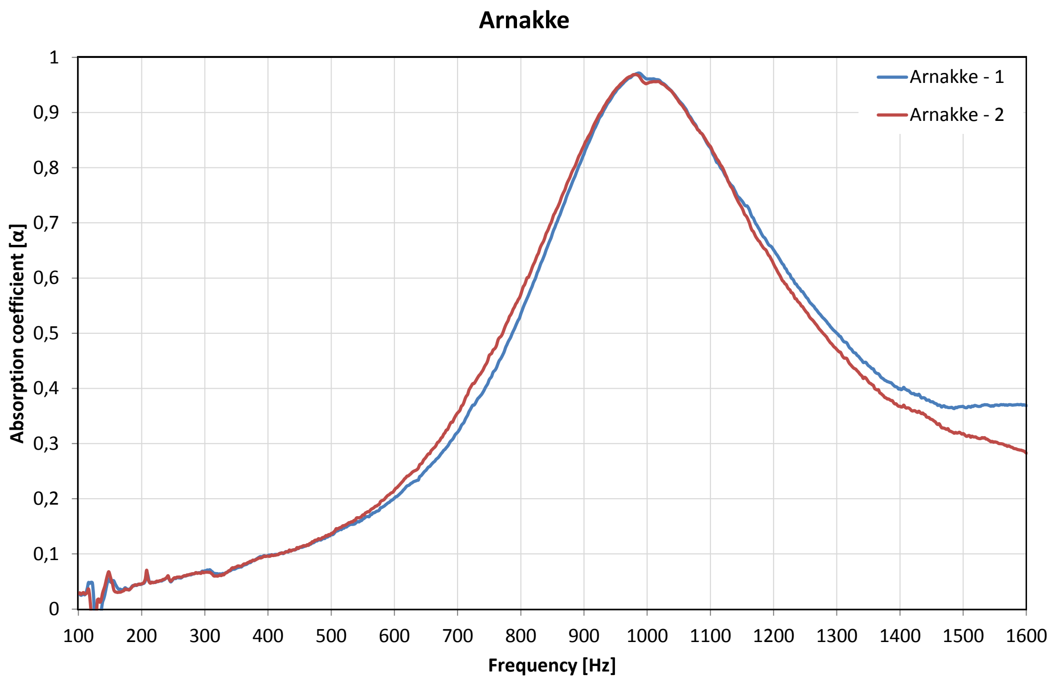


Figure 4.2:
FFT absorption spectre from the two Arnakke cores, in frequency range 100-1600 Hz.

The graphs in Figure 4.2 to 4.6 illustrate the absorption spectre from the cores of the different surfaces. The two cores from Arnakke (see Figure 4.2) have almost identical spectre from 100-1300 Hz, and a small deviation from 1300-1600 Hz. The maximum value is at 1000 Hz with a maximum absorption coefficient at 0.97. The six cores from Kalvehave (see Figure 4.3) has similar spectre, core number 2, 3, 4 and 6 have the same maximum absorption coefficient, whereas number 1 and 5 has a bit lower. The four cores from Linköping (see Figure 4.4) have some similarities in the shape of the spectre, but all of them deviate in maximum absorption coefficient and peak frequency. The three cores from Sterrebeek has similar spectre (see Figure 4.5).

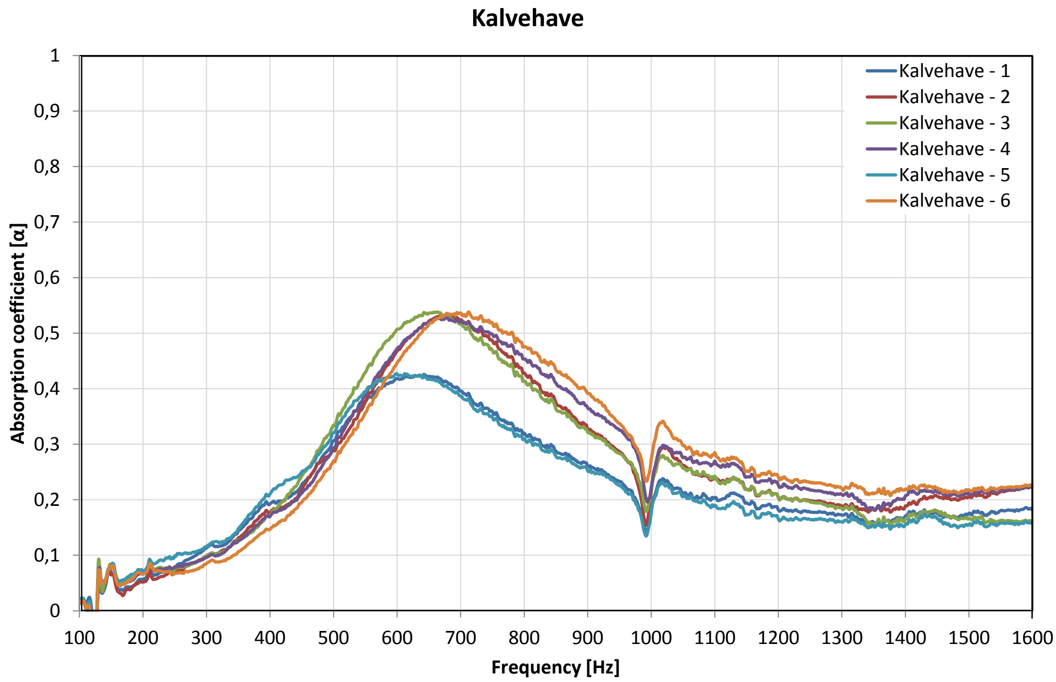


Figure 4.3:
Narrow-band absorption spectre from the six Kalvehave cores, in frequency range 100-1600 Hz.

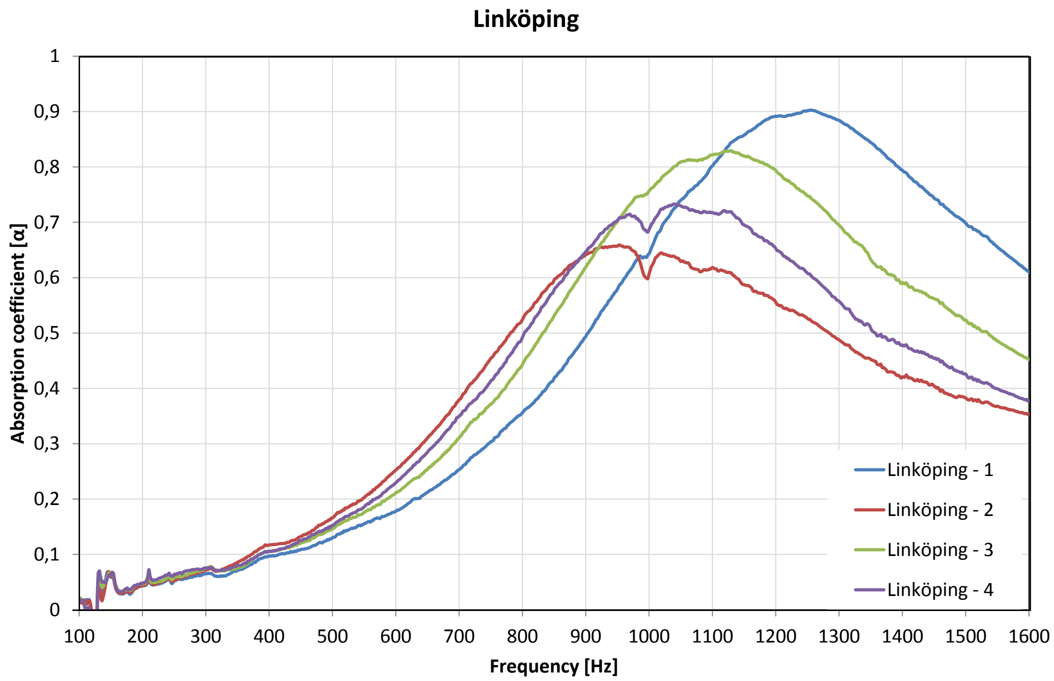


Figure 4.4:
Narrow-band absorption spectre from the four Linköbing cores, in frequency range 100-1600 Hz.

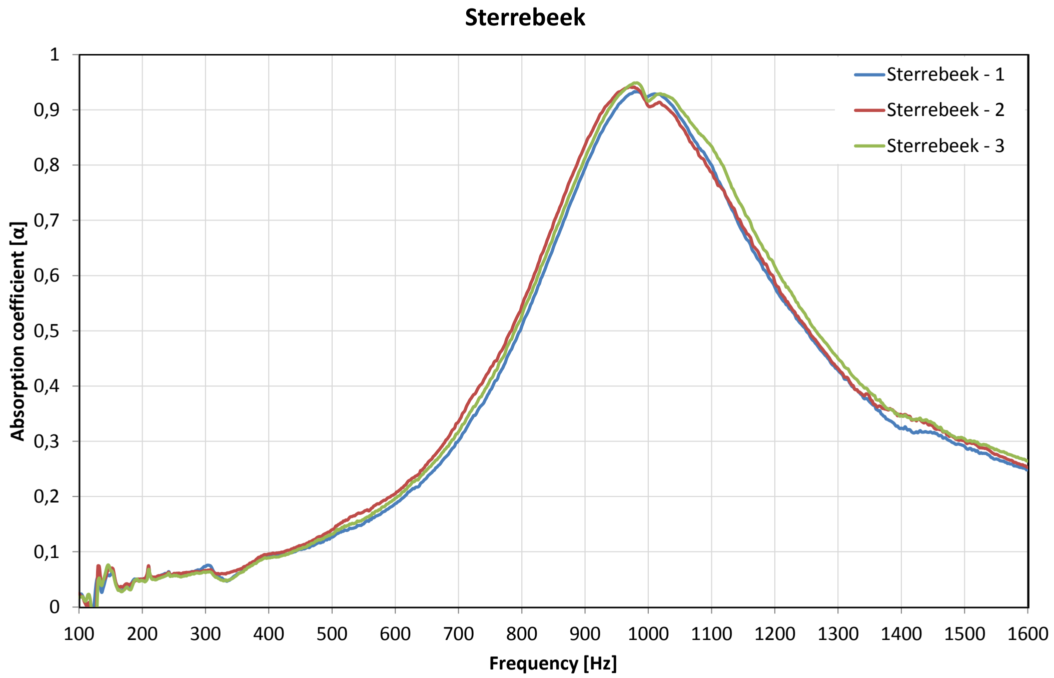


Figure 4.5:
Narrow-band absorption spectre from the three Sterrebeek cores, in frequency range 100-1600 Hz.

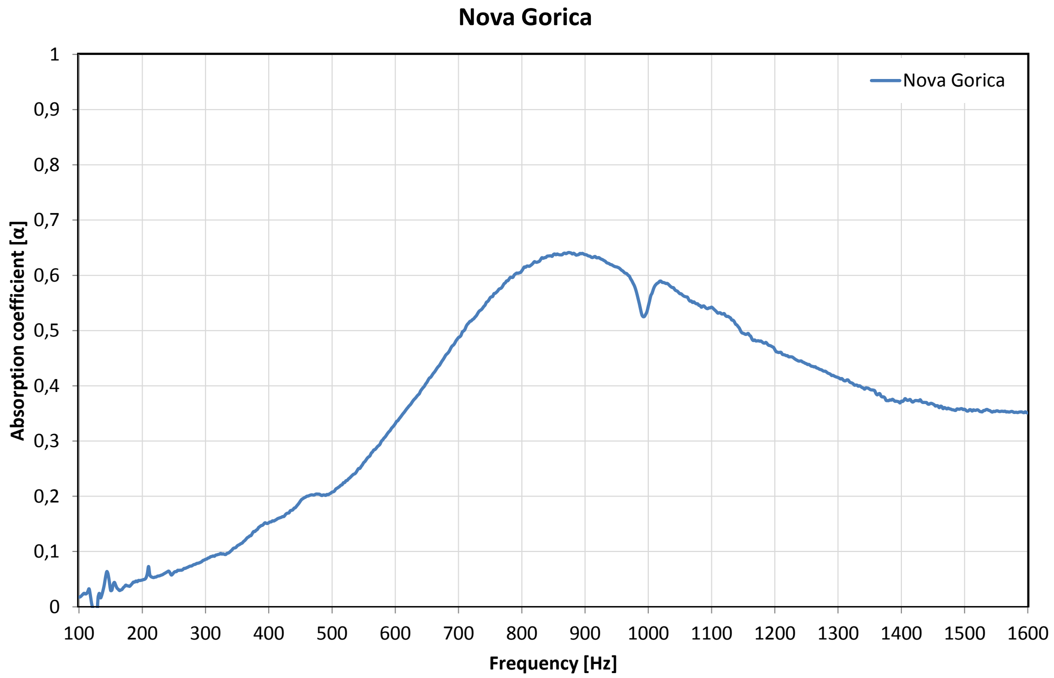


Figure 4.6:
Narrow-band absorption spectre from the core from Nova Gorica, in frequency range 100-1600 Hz

The peak frequencies and maximum absorption coefficients of the individual cores are illustrated in Table 4.1.

Table 4.1:
Peak frequency and maximum absorption coefficient of the different cores.

	Kalvehave						Arnakke		Nova Gorica	Sterrebeek			Linköping			
	#1	#2	#3	#4	#5	#6	#1	#2		#1	#2	#3	#1	#2	#3	#4
Frequency [Hz]	640	676	655	670	610	695	985	980	875	995	970	980	1250	925	1125	1040
α_{max}	0.43	0.53	0.54	0.53	0.43	0.54	0.97	0.97	0.64	0.93	0.94	0.95	0.90	0.66	0.83	0.73

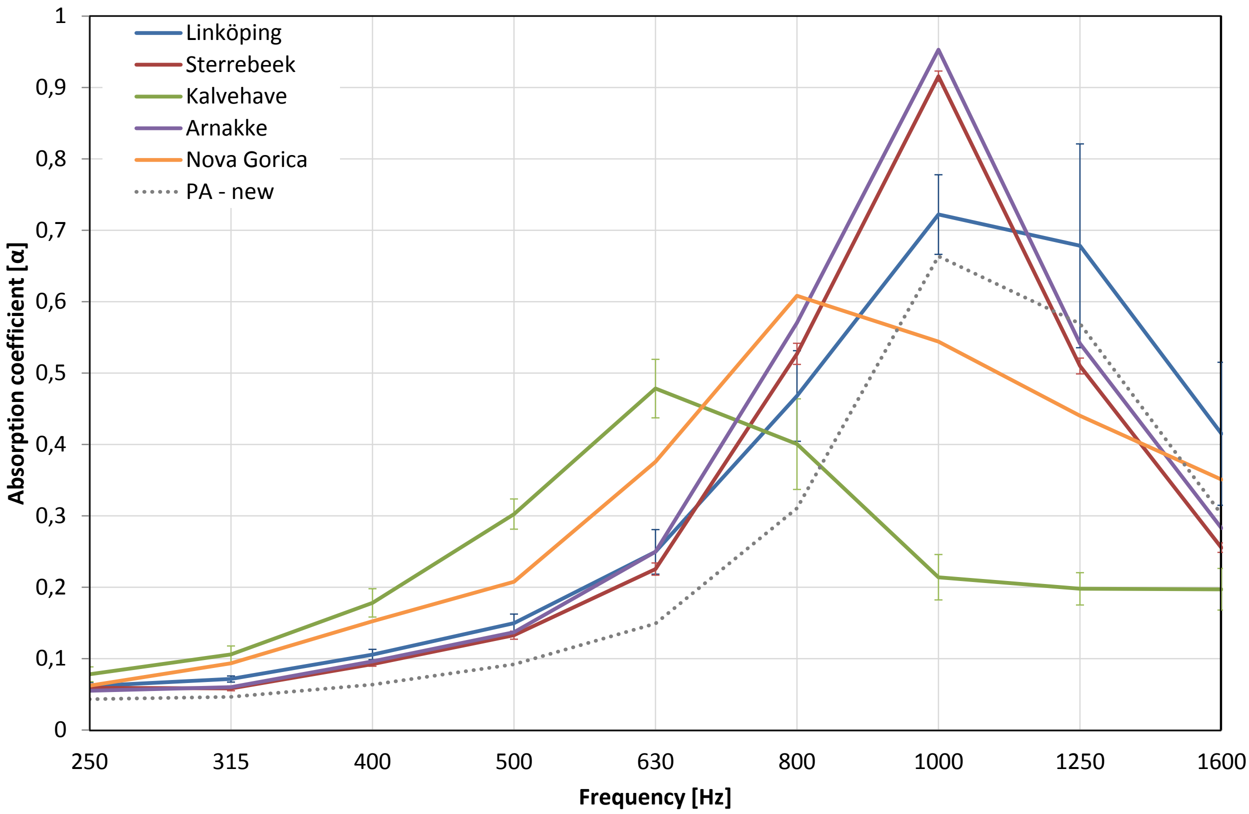


Figure 4.7:
Average absorption spectrums in 1/3 octave bands for the different pavements, including a new porous asphalt (PA-new). The Nova Gorica pavement is not an average, but a single core. The bars show the standard deviations.

Average absorption spectrums of the different pavements in one-third octave bands are illustrated in Figure 4.7. The figure illustrates that the spectrums from Sterrebeek and Arnakke are similar, with a high absorption coefficient in the 1000 Hz band. The spectrum from Linköping has some high standard deviations in the high frequencies of the spectra, and similarities to the porous asphalt illustrated. The spectre from Nova Gorica has a peak value in the 800 Hz band which is the second lowest peak frequency and value. The spectre from Kalvehave has a peak value in the 630 band, which is at the lowest peak frequency and the lowest absorption coefficient. The new porous asphalt cores included in Figure 4.7 is an average measurement of two cores from the Arnakke test site [2]. The design goal is to get the maximum absorption between 600 and 1000 Hz and this goal has been reached for all the test pavements according to these absorption measurements on cores from the test slabs.

5. Built in air void

The plane sections are prepared from a slice of material cut from a test slabs as can be seen in the figures below. These slices are impregnated with epoxy resin containing fluorescent dye. The size of the plane sections corresponds to the width and height of the samples and the thickness is approximately 10 mm.

All the plan sections of the test slabs under incident UV-light can be seen in Figure 5.1 to 5.4. The air voids filled with epoxy resin will under these conditions light up like a bright green colour. It can be seen that there is an even distribution of rubber aggregates and stone aggregates at all levels (surface, middle and bottom) of the four test samples. The air voids have been measured on 3 plane sections of the same material except for the Nova Gorica material where only one section was used. For practical reasons the Arnakke slab was not included.

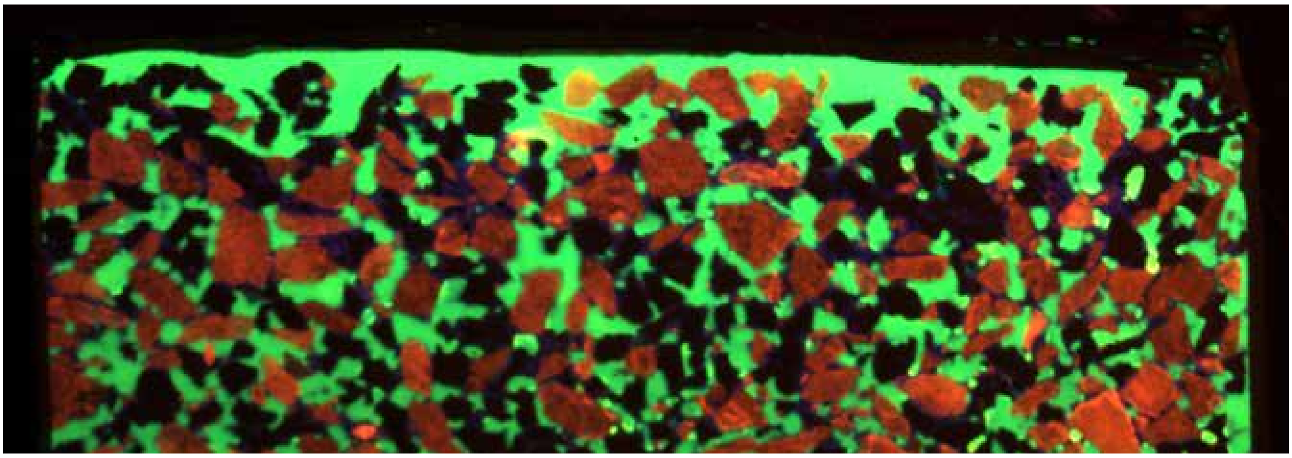


Figure 5.1:
Plane section of the Kalvehave test slab. The green areas are air voids, the black areas are rubber aggregates and the red areas are stone aggregates.

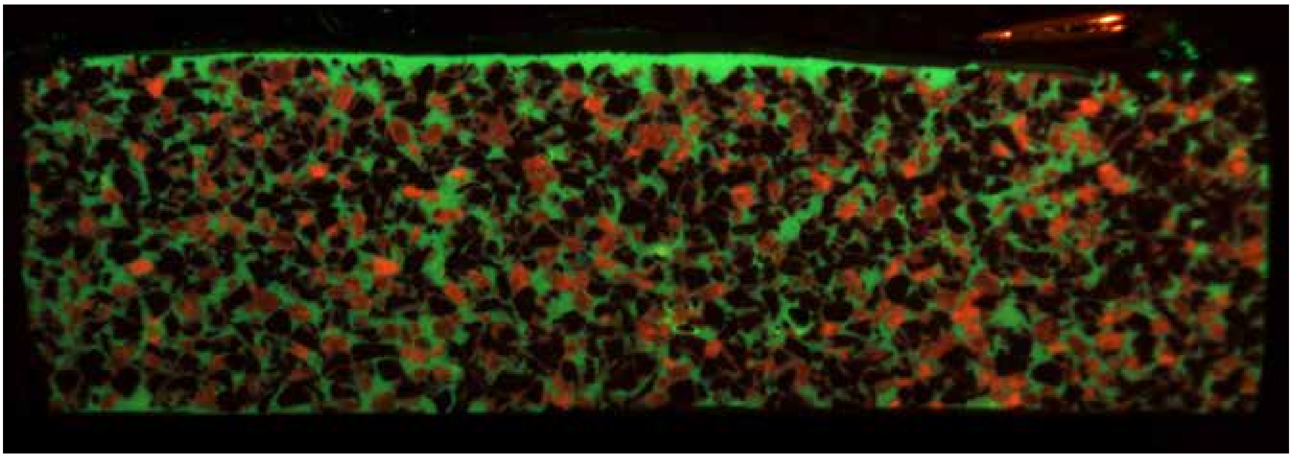


Figure 5.2:
Plane section of the Nova Gorica test slab. The green areas are air voids, the black areas are rubber aggregates and the red areas are stone aggregates.

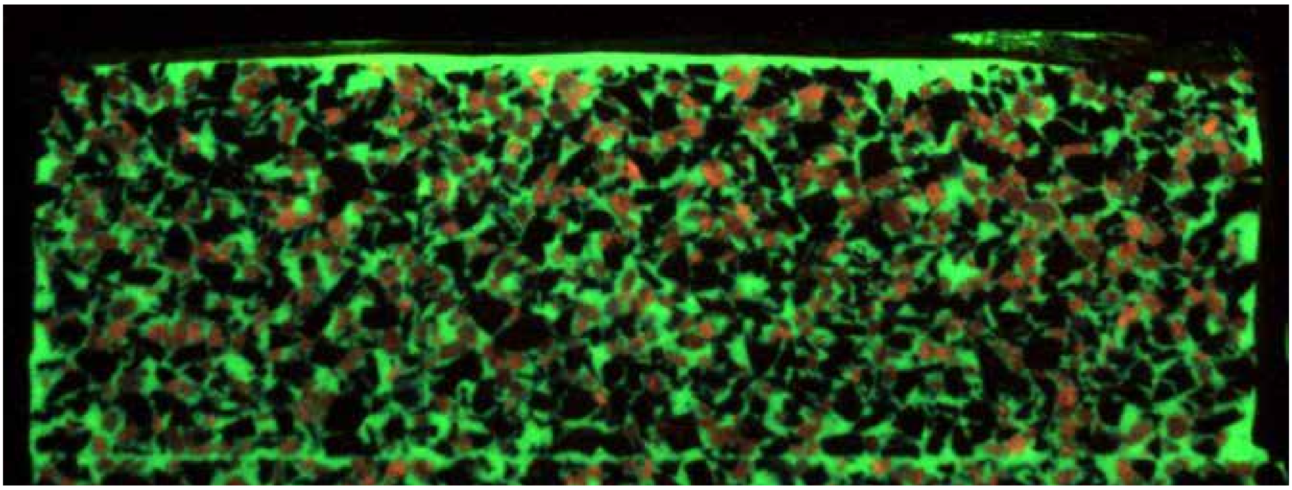


Figure 5.3:
Plane section of the Linköping test slab. The green areas are air voids, the black areas are rubber aggregates and the red areas are stone aggregates.

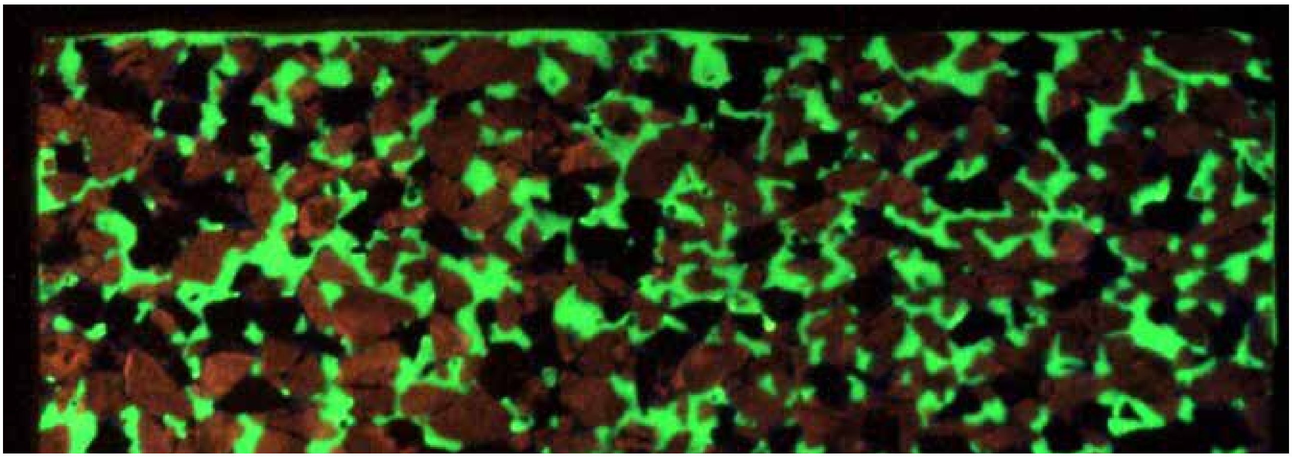


Figure 5.4:
Plane section of the Sterrebeek test slab. The green areas are air voids, the black areas are rubber aggregates and the red areas are stone aggregates.

Table 5.1:
Air voids in test slabs measured by image analysis on plane sections.

Test slab	Measured air void [%]	Average [%]
Arnakke	Not measured	-
Kalvehave	29.5	27.7
	25.6	
	28.1	
Nova Gorica	31.0	31.0
Linköping	23.4	26.2
	25.4	
	29.8	
Sterrebeek	21.9	21.4
	22.4	
	19.8	

The content of air voids were measured by image analysis and the results for each test slabs can be seen in Table 5.1. For the air void of two-layer porous pavements at the Danish Øster Søgade test site was 23 to 27 % when new [6]. The target air void for the PERS mix has been estimated to be 30 %. Generally the air void is quite high and around the target level for the Kalvehave, Nova Gorica and Linköping test slabs and a less for the Sterrebeek test slab.

6. Surface texture

The texture of the surfaces was measured with the in-situ laser device illustrated in Figure 6.1. The DRD in-situ texture laser records profiles of 1.5 m parallel lines separated with 1 cm. The resolution of the instrument is 0.1 mm in the length direction (x) and 9 µm in the height direction(z). The laser is an LMI Selcom SLS5000 with 16 kHz sampling frequency and a spot size of 0.1 mm. The measurements of the Arnakke and Kalvehave surfaces are measured at the actual test site pavements, whereas the Linköping and Sterrebeek are measured in the laboratory on test slabs. As reference are an old asphalt concrete and a new porous asphalt located at Arnakke and a new stone mastic asphalt located nearby Roskilde measured. The measurements at Arnakke are performed with a sample distance of 0.5 mm, and the other measurements with a sample distance of 0.18 mm. The in-situ laser measuring at the Kalvehave test site is illustrated in Figure 6.1.

For each recorded profile the mean profile depth (MPD) was determined per 100 mm according to the ISO 13473-1 standard. Figure 6.2 to 6.6 illustrates the average MPD along the different test surfaces. Some of the surface at Arnakke was in bad condition, and this part is marked with a dotted line (see Figure 6.2). The texture at the Kalvehave test section has been measured at 5 different positions along the test section (9 m, 24 m, 39 m, 54 m, and 69 m starting at the east end of the test section). It can be seen that the MPD at the 54 m position is remarkably higher than at the other positions. It has been decided not to include the 54 m position when predicting the average MPD for the test pavement.

At the test slabs from Linköping and Sterrebeek (see Figure 6.4 and 6.5) are some parts of the lines also marked with dotted lines, which is due to MPD measurements crossing surface in bad condition or the edge of the test slabs. The sections dotted in the MPD graphs are not included in texture spectrum recordings.

MPD per 100 mm of three surfaces Stone Mastic Asphalt (SMA6+8-new), Asphalt Concrete (AC11d-old) and Porous Asphalt (PA-new) are presented in Figure 6.6. These results can be used for comparison.

The figures illustrates that there are some variations in the individual lines, and that there are some differences in the average MPDs of the different surfaces.

Figure 6.1:
Texture measurements performed at the Kalvehave test site.

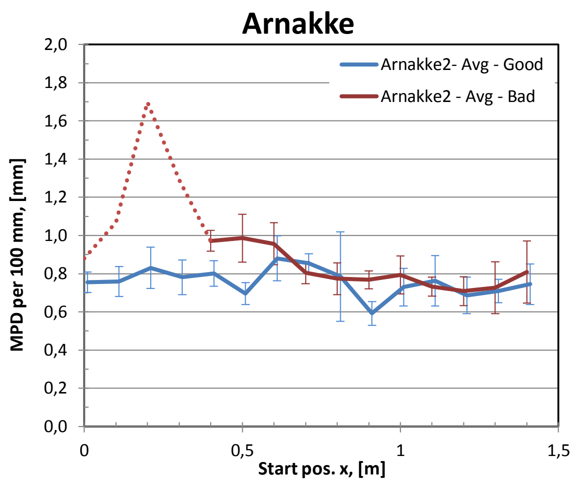


Figure 6.2:
MPD per 100 mm of the Arnakke test surface of a position in a good and a position in a bad condition. Numbers are averages of 3-5 parallel lines, illustrated with standard deviations. Dotted lines where the surface measured in a bad condition.

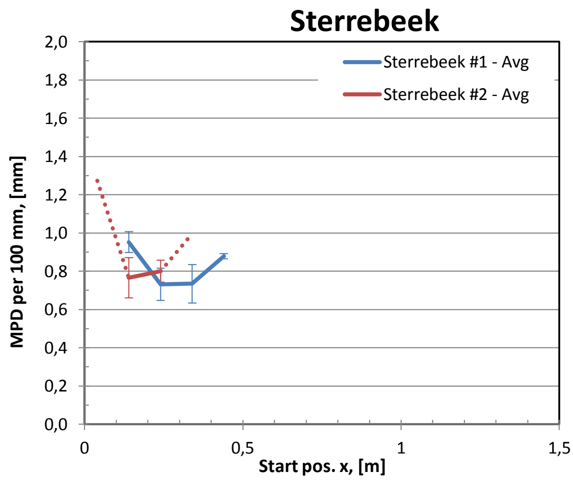


Figure 6.5:
MPD per 100 mm of the Sterrebeek test slab. Numbers are averages of 3-5 parallel lines, illustrated with standard deviations. Dotted lines where the measurement is also performed across the edge of the test slabs.

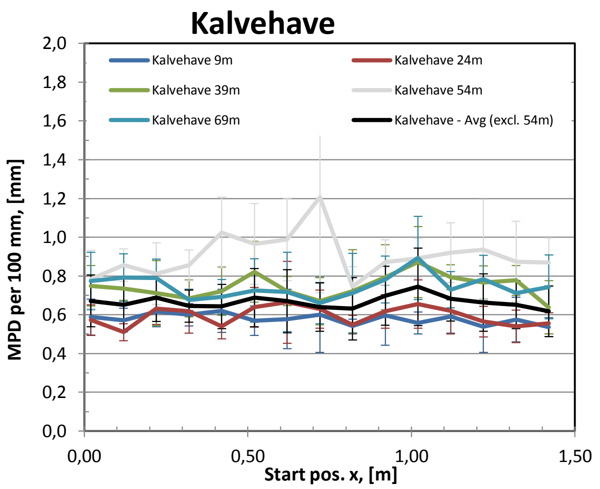


Figure 6.3:
MPD per 100 mm of the Kalvehave test surface measured at different locations at the actual test pavement. Numbers are averages of 3-5 parallel lines, illustrated with standard deviations.

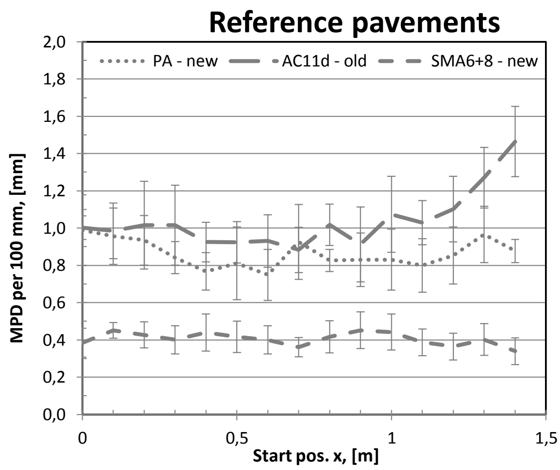


Figure 6.6:
MPD per 100 mm of three surfaces that can be used for comparison; Stone Mastic Asphalt (SMA6+8-new), Asphalt Concrete (AC11d-old) and Porous Asphalt (PA-new). Numbers are averages of 3-5 parallel lines, illustrated with standard deviations.

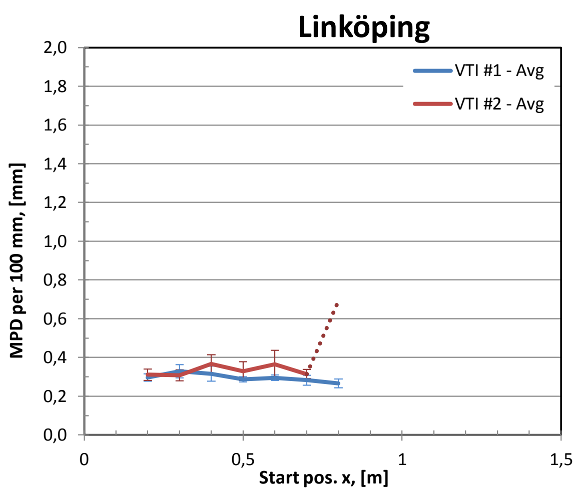


Figure 6.4:
MPD per 100 mm of the Linköping test slab. Numbers are averages of 3-5 parallel lines, illustrated with standard deviations. Dotted lines where the measurement is across the edge of the test slabs.

Table 6.1:
Average MPD of different surfaces. Values are averages of parts of surfaces in good condition. The 54 m position at Kalvehave is excluded.

Surface type	Arnakke	Kalvehave Avg.	Linköping	Sterrebeek	PA new	AC11d old	SMA6+8 new
Average MPD [mm]	0.79	0.67	0.31	0.80	0.86	0.96	0.41

The average MPD for the individual surfaces are illustrated in Table 6.1. The table and the graphs above show that the MPDs of Arnakke and Sterrebeek surfaces are of the same level of 0.8 mm, Kalvehave with 0.67 mm a little bit lower, and Linköping with 0.31 mm significantly lower.

The average texture spectrums from the different surfaces are illustrated in Figure 6.7 to 6.10. The spectrums are averages of 3-5 parallel lines, illustrated with the standard deviations. The averages are of similar shapes and magnitudes within the surfaces, but the Kalvehave 54 m position has a significant deviation from the other spectres from Kalvehave.

Average texture levels of the different pavements are illustrated in Figure 6.11. The figure illustrates that Sterrebeek and Kalvehave has similar texture spectre. The Arnakke texture level is similar to Sterrebeek and Kalvehave from 100-4 mm, but deviates from 4-1 mm. These three pavements all have a maximum aggregate size of 5 mm.

The Linköping texture level deviates significantly from the three other surfaces. The Linköbing test slab has a maximum aggregate size of 3 mm.

None of the texture levels of the four PERS surfaces are like the surfaces the three pavements included for comparison (SMA6+8, AC11d and PA), but Sterrebeek and Kalvehave have the same shape as the SMA with a maximum aggregate size of 6 mm, but with magnitude shift.

For the macro texture, the goal has been to get a high texture level at the short wavelengths and a low texture level at the longer wavelengths. This has generally been achieved for the test slabs.

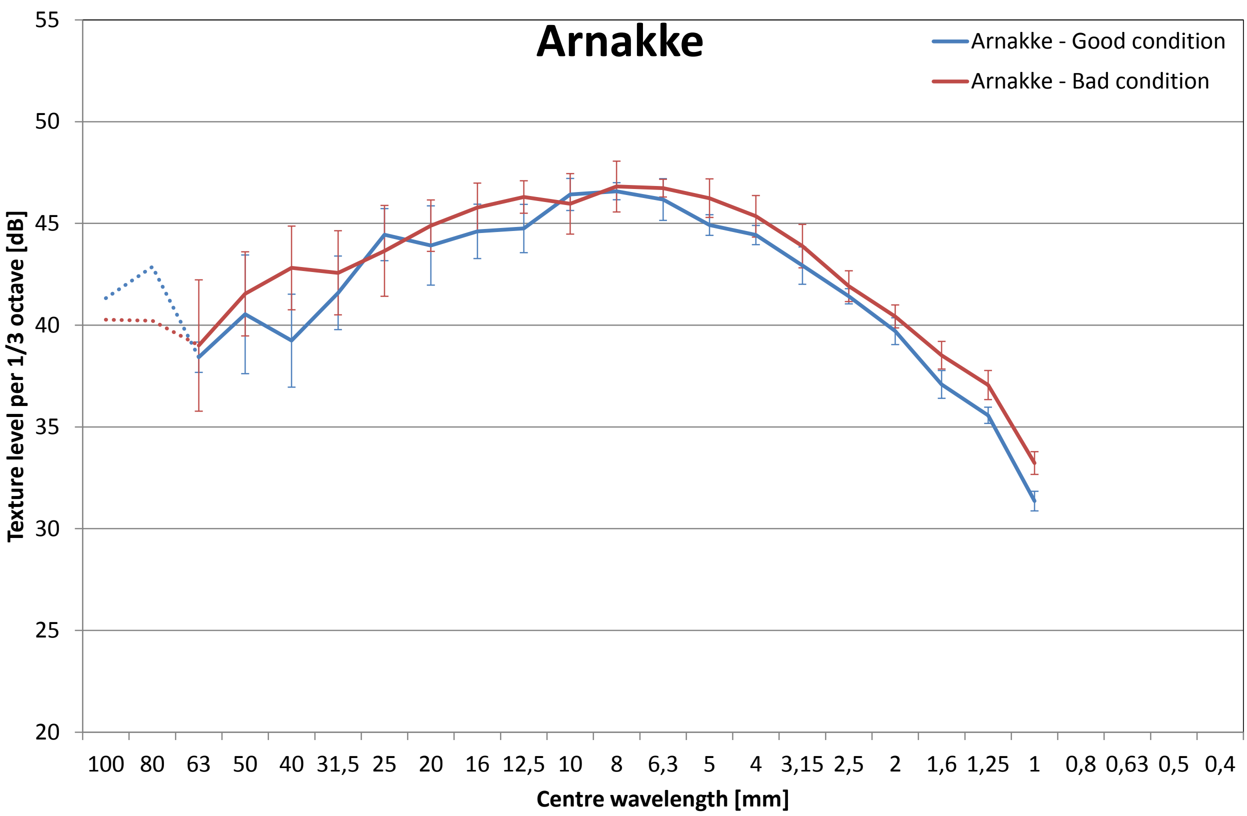


Figure 6.7:
Average texture levels at the Arnakke test section in 1/3 octave bands of measurements of a position in a good and a position in a bad condition, including standard deviation. Numbers are averages of 3-5 parallel recorded lines. The dotted part of the spectrums represents measurements outside the valid range.

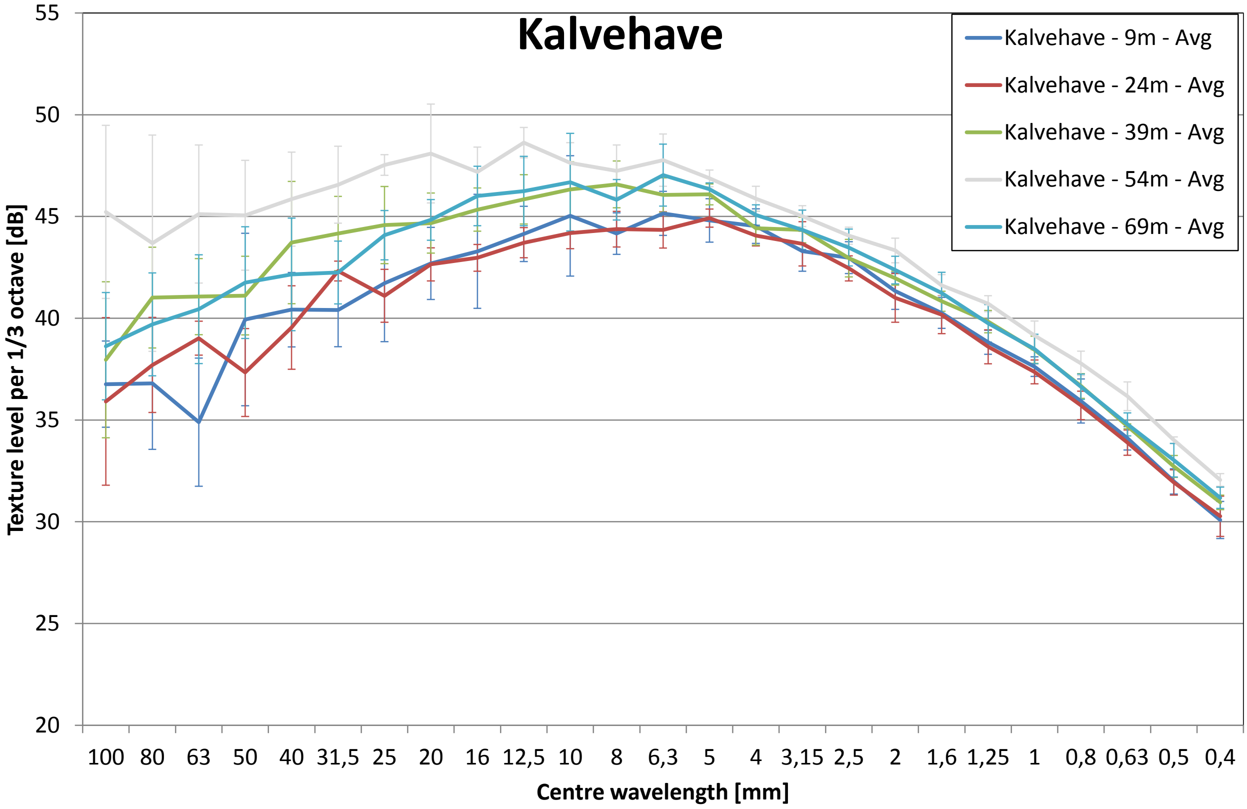


Figure 6.8:
Average texture levels at the Kalvehave test section in 1/3 octave bands of measurements in 5 positions along the test section, including standard deviation. Numbers are averages of 3-5 parallel recorded lines.

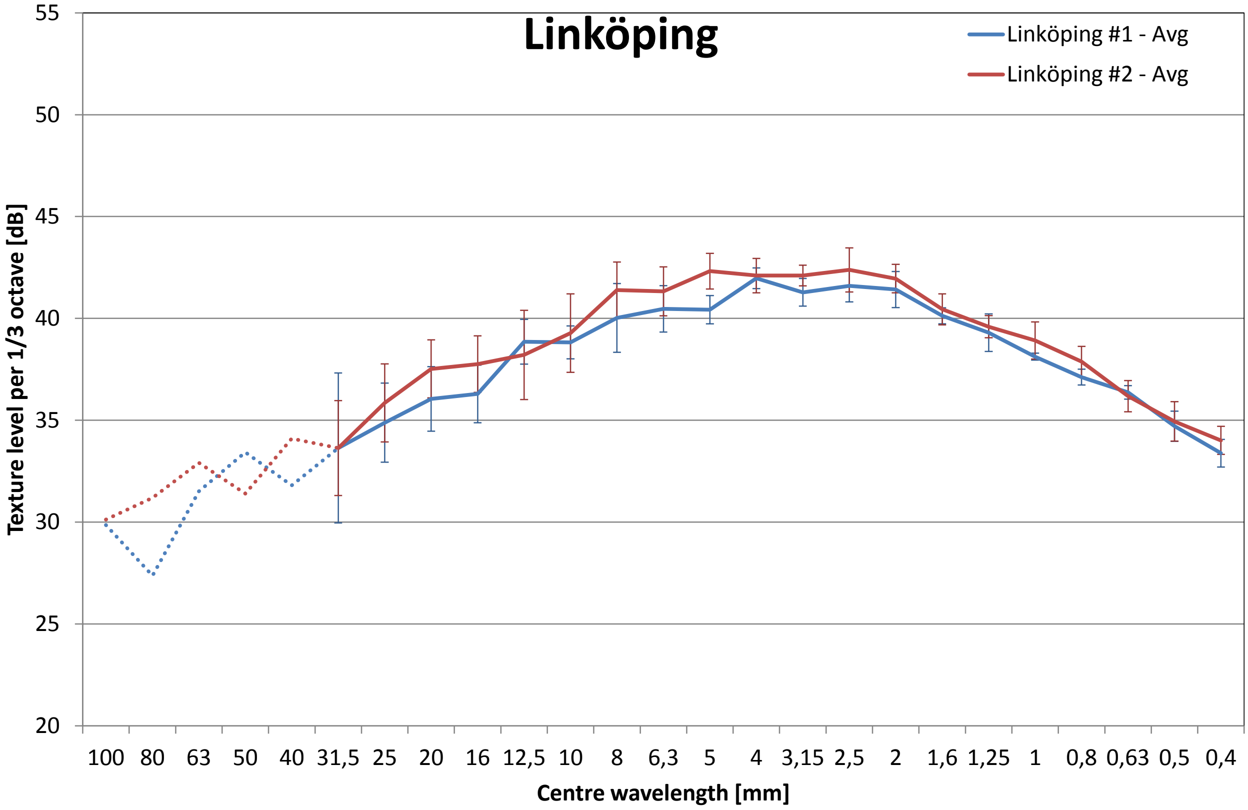


Figure 6.9:
Average texture levels on the Linköbing test slab in 1/3 octave bands of two measurements, including standard deviation. Numbers are averages of 3-5 parallel recorded lines. The dotted part of the spectrums represents measurements outside the valid range.

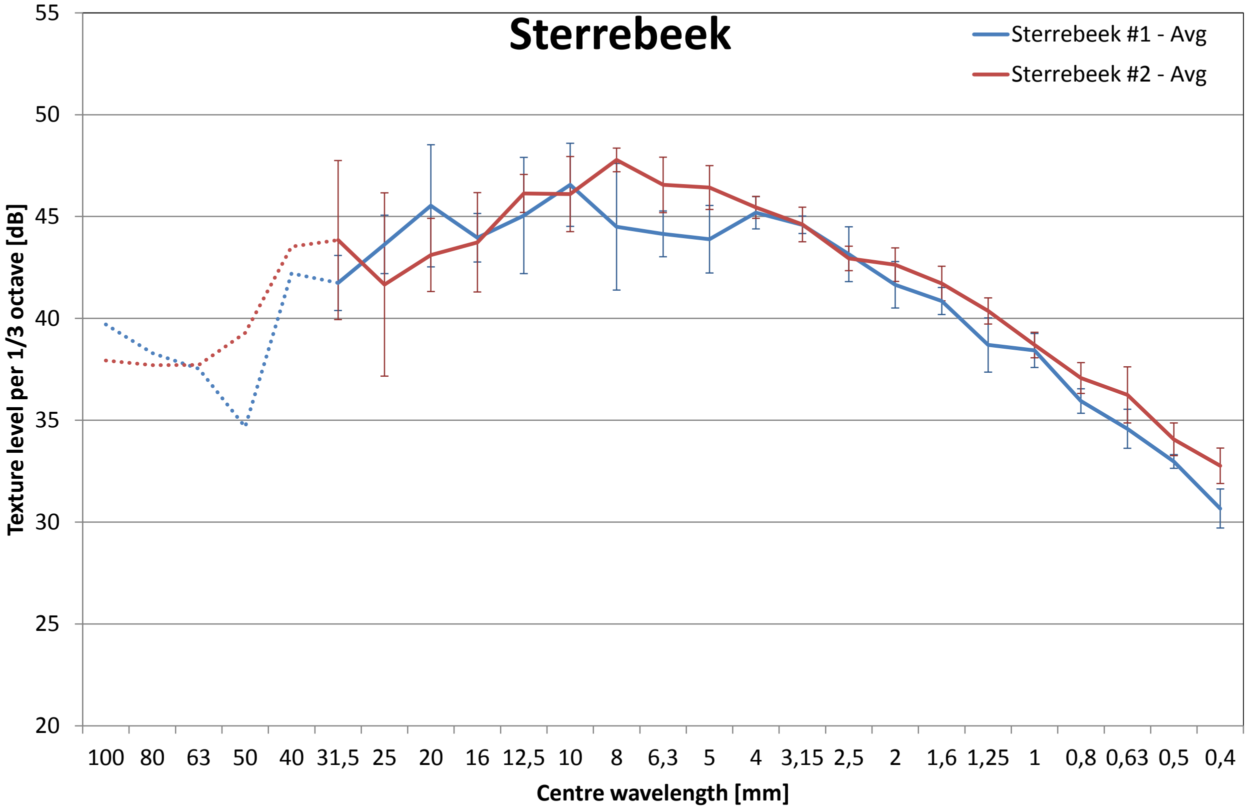


Figure 6.10:
Average texture levels on the Sterrebeek test slab in 1/3 octave bands of two measurements, including standard deviation. Numbers are averages of 3-5 parallel recorded lines. The dotted part of the spectrums represents measurements outside the valid range.

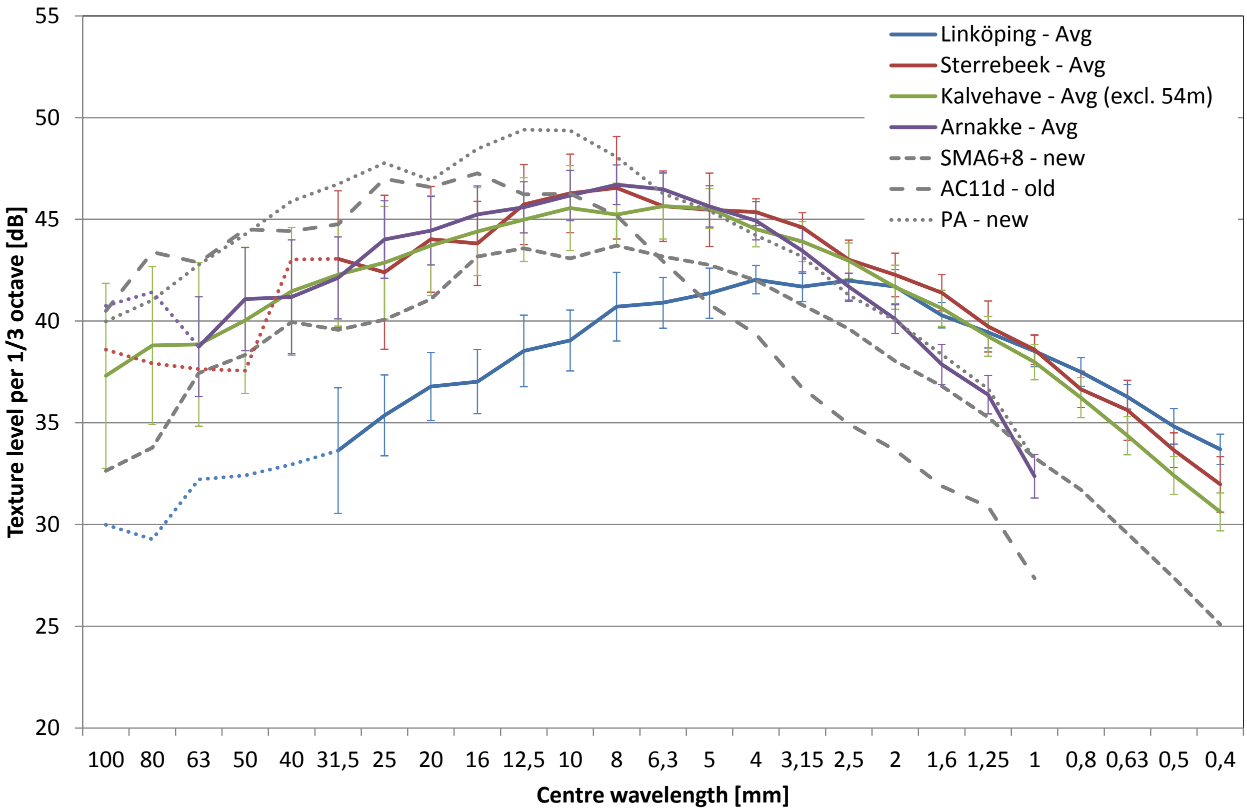


Figure 6.11:
Average texture levels of the different surfaces in third octave bands, illustrated with standard deviations. Stone Mastic Asphalt (SMA6+8-new), Asphalt Concrete (AC11d-old) and Porous Asphalt (PA-new) are included for comparison. The dotted part of the spectrums at Arnakke, Linköping and Sterrebeek represents measurements outside the valid range.

7. Mechanical impedance

The measurement principle of the mechanical impedance of PERS is illustrated in Figure 7.1. The experimental setup is composed of a hammer delivering an impact force $f(t)$, an impedance head measuring the direct force $f_d(t)$ and the direct acceleration $a_d(t)$ at the impact location and an accelerometer measuring the transferred acceleration $a_t(t)$ at a certain distance from the impact point.

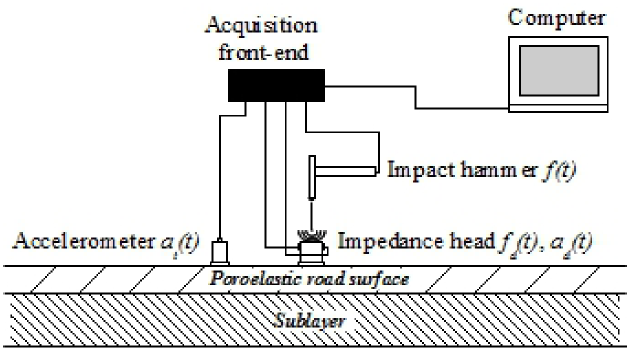


Figure 7.1:
Measurement principle of the mechanical impedance of PERS.

Defining the Fourier transform of a signal $x(t)$ by $X(\omega)$ with ω the angular frequency, the direct mechanical impedance Z_d is obtained by FFT analysis on the measured signals:

$$Z_d(\omega) \stackrel{\text{def}}{=} \frac{F(\omega)}{V_d(\omega)} = \frac{j\omega F(\omega)}{A_d(\omega)} = |Z_d(\omega)|\, e^{j\phi_{Z_d}(\omega)} \qquad (7.1)$$

where $|V_d(\omega)|$ is the direct velocity, $|Z_d(\omega)|$ is the magnitude of Z_d and $\phi_{Zd}(\omega)$ its phase. The transfer mechanical impedance $Z_t(\omega)$ can be defined similarly.

The equipment for testing mechanical impedance can be viewed in Figure 7.2 together with the operator and is composed of an impact hammer, an impedance head mounted between two circular steel plates and an accelerometer mounted on a hexagonal base. The sensors are connected to the acquisition system composed of a laptop computer and a Bruël & Kjaer acquisition front-end of type 3560C.

Both sensors were stuck on the road surface with superglue HBM X60 (Figure 7.3). The distance between the accelerometer (transfer point) and the impedance head (direct point) was fixed to 10 cm. The experimental protocol consists in a succession of six impacts on the impedance head using the impact hammer. Each impact is carefully validated by the operator during the test. The transfer function between the impact force and the acceleration is calculated after averaging the spectra of the six signals. The direct and transfer mechanical impedances can then be obtained using equation (7.1). The test was repeated several times at each spot or sample in order to check the repeatability.

The mechanical impedance was tested on the PERS of the 5 test sites. Danish sections (Arnakke and Kalvehave) were directly tested on site. One spot was tested in June 2012 on the small PERS test section in Arnakke, while five different spots were tested on the PERS test section in Kalvehave in October 2013 (see Figure 7.4).

The mechanical impedance for the other sites was measured on PERS samples in laboratory in March 2014 (see Figure 7.5). Three samples of the Nova Gorica test site were

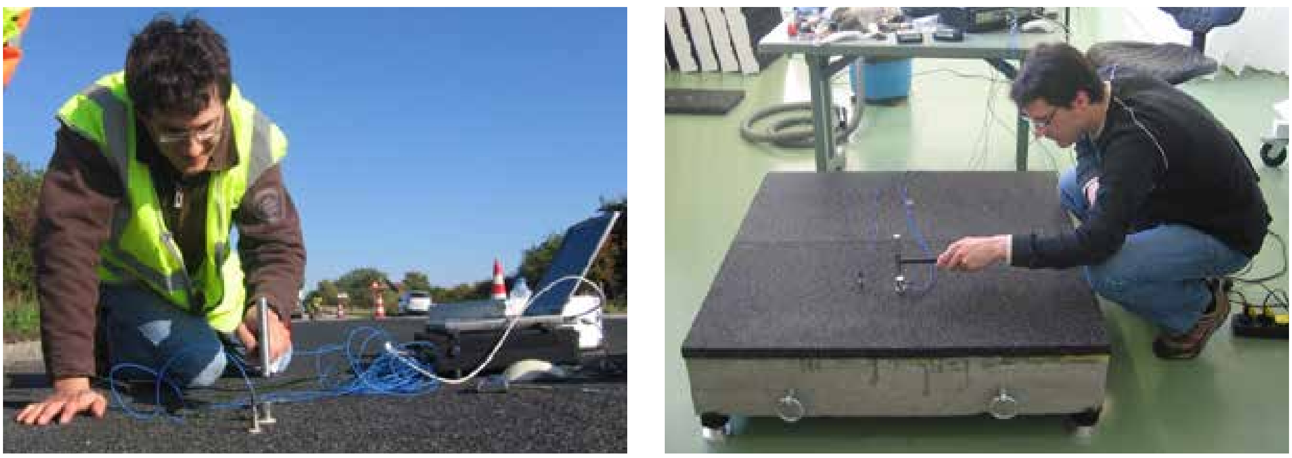


Figure 7.2:
IFSTTAR performing mechanical impedance measurements on PERS pavement at the Kalvehave test site and in laboratory at Nantes (France) on Linköping test site samples glued on a 1m by 1m concrete block.

tested. Each sample was composed of a PERS sample glued on a concrete paving block by ZAG. The samples were just laid over the 1m by 1m concrete base during the test. Then, two 1m by 0.5m samples of the Linköping test site were sent by VTI to IFSTTAR. The samples were glued on the 1m by 1m concrete base with a polyurethane binder (Sikaflex 11 FC) before performing the test. The same procedure was followed for the 0.54m by 0.32m sample from Sterrebeek which was sent by BRRC to IFSTTAR.

Figure 7.3:
Positions of the sensors on the PERS after gluing (left: accelerometer, right: impedance head).

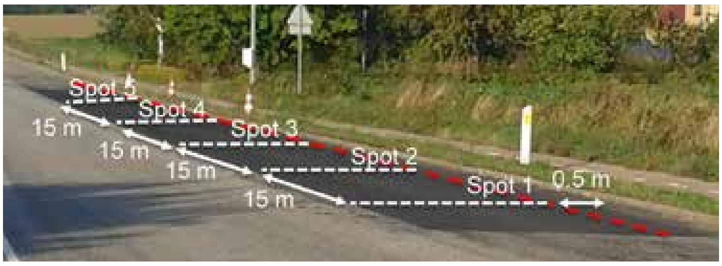


Figure 7.4:
Location of the spots for mechanical impedance testing on the PERS section in Arnakke (left, 1 spot) and in Kalvehave (right, 5 spots).

Figure 7.5:
Mechanical impedance testing of PERS samples in laboratory. The Nova Gorica samples (left, PERS glued on a concrete paving block) were just laid over the 1m by 1m concrete base during the test. Linköping (middle) and Sterrebeek (right) samples were glued on the concrete base with a polyurethane binder (Sikaflex 11 FC).

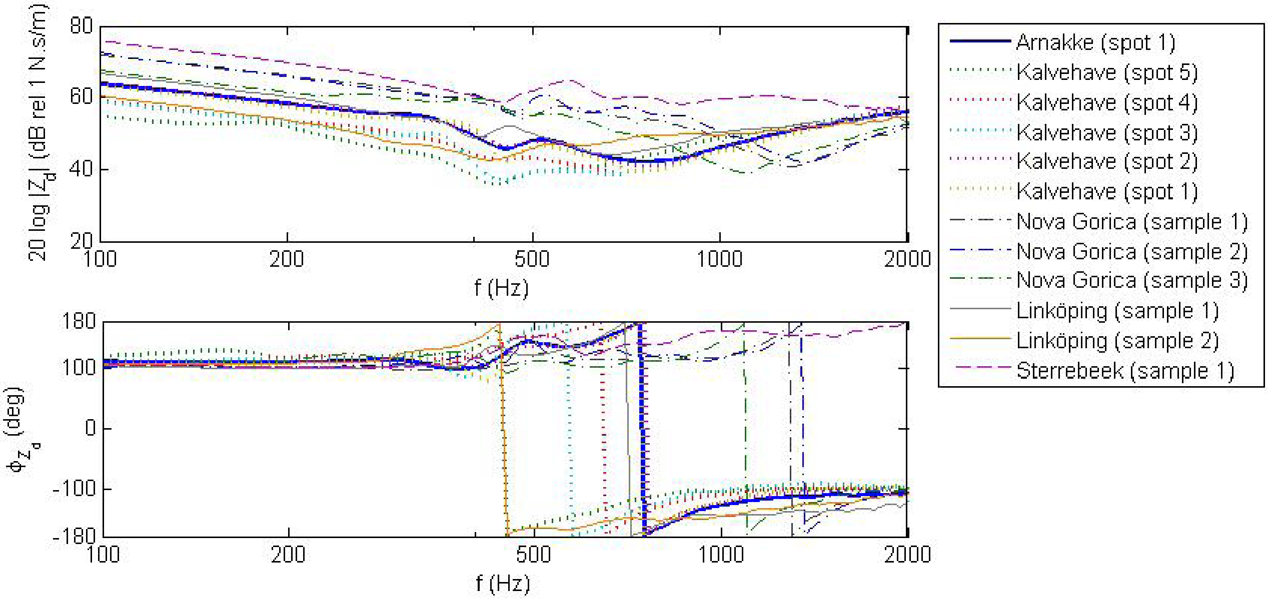


Figure 7.6:
Direct mechanical impedance from all the slabs, including on site measurements (Arnakke and Kalvehave test sites) and laboratory measurements (Nova Gorica, Linköping and Sterrebeek).

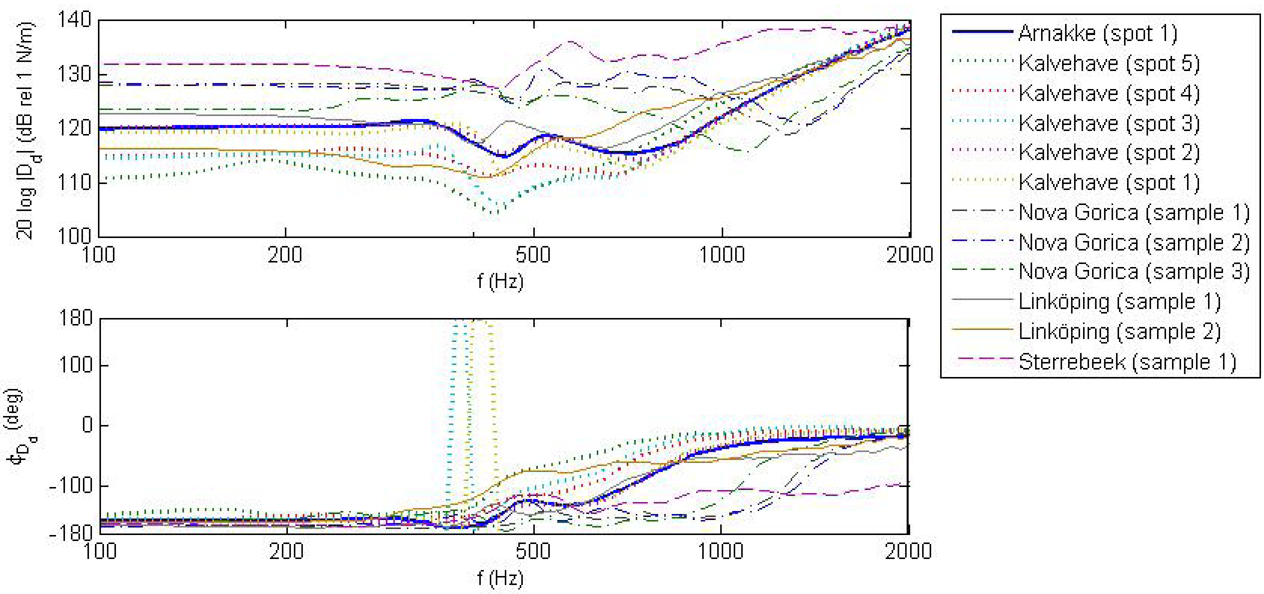


Figure 7.7:
Direct dynamic stiffness from all the slabs, including on site measurements (Arnakke and Kalvehave test sites) and laboratory measurements (Nova Gorica, Linköping and Sterrebeek).

The direct mechanical impedance is given in Figure 7.6 for the five test sites. Each curve represents the result of a test obtained from a series of six impacts. The magnitude of the mechanical impedance is given in dB relative to 1 N.s/m and the phase is given in degrees. The curves at the different test sites have quite similar shapes. At low frequency, there is a linear decrease of the mechanical impedance which is typical of an ideal spring. At high frequencies, there is a linear increase of the mechanical impedance which is typical of an ideal mass. At medium frequencies, there is a minimum value at a frequency corresponding to the resonance of the mass spring system. The minimum value corresponds to the damping of the system. At the resonance frequency a typical phase shift is also observed.

The magnitude differences observed in Figure 7.6 can be qualitatively assessed from a simple Single Degree Of Freedom (SDOF) system consisting in a mass m over a parallel spring/dashpot combination. The stiffness of the spring is denoted k while the damping constant of the dashpot is denoted *c*. The natural frequency of such a system is $f_0=\sqrt{(k/m)}$.

The SDOF parameters can be assessed manually from the experimental data. First the natural frequency f_0 is determined from the phase shift in Figure 7.6. Then the damping constant *c* is estimated from the magnitude value of the mechanical impedance in Figure 7.6, which is close to the minimum value. The stiffness *k* is estimated from the value of the dynamic stiffness D_d at low frequency, i.e. between 100 Hz and 200 Hz. The dynamic stiffness can be derived from the mechanical impedance and is depicted in Figure 7.7. Finally the mass m can be easily calculated from the estimates of f_0 and *k*.

The dynamic Young's modulus E of the PERS can be estimated from the dynamic stiffness *k*:

$$E=\frac{kh}{\pi r^2} \qquad (7.2)$$

where *h* is the thickness of the PERS assumed to be homogenous and *r* = 0.01 m is the radius of the circular steel plates glued on the PERS. The PERS thickness for each test site is given in Table 1.1. Table 7.1 gives the values of the dynamic Young's modulus for each spot or sample. For a given surface, some differences are observed. These could be explained by a lack of homogeneity of the materials. The small contact area between the impedance head and the PERS may also explain the differences because a local property is measured. The average value of E in increasing order is 63.6±26.4 MPa for Kalvehave test site, 95.5 MPa for Arnakke test site, 102.0±50.1 MPa for Linköping samples, 207.5±56.1 MPa for Nova Gorica samples and 526.1 MPa for Sterrebeek sample. The ratio is about 8 between the softer and the stiffer PERS, while it would be between 30 and 250 if the PERS were compared to a very stiff Dense Asphalt Concrete (E≅ 15000 MPa).

Table 7.1:
Estimated dynamic Young modulus for each test site.

Test site	E [MPa]	T_{surf} (°C)	<E> [MPa]
Arnakke	95.5	22.3	95.5
Kalvehave	85.1	24.0	63.6 ± 26.4
	95.5	23.5	
	53.7	18.0	
	53.7	21.5	
	30.2	12.5	
Nova Gorica	237.1	17.6	207.5 ± 56.1
	242.6	18.9	
	142.9	21.0	
Linköping	137.4	21.4	102.0 ± 50.1
	66.5	22.5	
Sterrebeek	526.1	18.9	526.1

8. Thin and plane section analysis

The thin section is taken from a piece cut vertically from the sample. An example illustrating this can be seen in Figure 8.1. The standard thin sections are impregnated with epoxy resin containing fluorescent dye which fills all air voids, porous rocks and cracks. When the epoxy has hardened, the subsample is cut very finely, parallel to the impregnated surface, to provide a thin section that is then finally planed so that it has a regular thickness. A prepared thin section has an area of approximately 35 x 45 mm^2. Normally thin sections have a thickness of approx. 20 µm. In this case, where it is a PERS surface which is produced with rubber granulate, the final thickness of the sections is approx. 90 µm so that the rubber is not pulled out during the final polishing of the thin section.

The thin sections are visually analyzed using a microscope. The microscope is also used to take images of the thin sections. Pictures from the microscopy can be seen in the photographs in the figures below. The different components (rubber, aggregate and polyurethane) are clearly distinguishable.

Visual investigations of the thin section under the microscope have been carried out with transmitted light. All the pictures from the microscopy of the thin section are seen in Annex A to E. Below in Figure 8-2 and 8-3 are two selected photos.

For the Arnakke slab two thin sections have been prepared from the sample. In the samples from Arnakke, photos taken in microscope (see Figure 8.2 and 8.3) reveal that the polyurethane mortar fills almost all voids and a satisfactory coating of the aggregates and rubber material has been obtained. In this sample the steel fibers from the rubber can also be seen. See also Annex A for more images from Arnakke.

In the following images of the different layers of four of the slabs are presented. Layer one is the surface of the slab and layers with higher numbers refers to positions deeper down in the test slab as is illustrated in Figure 8.4. For practical reasons the Arnakke test slab has not been investigated in this way.

The air voids are yellow, rubber is black, the stone aggregates are grey and the polyurethane mortar is also greyish.

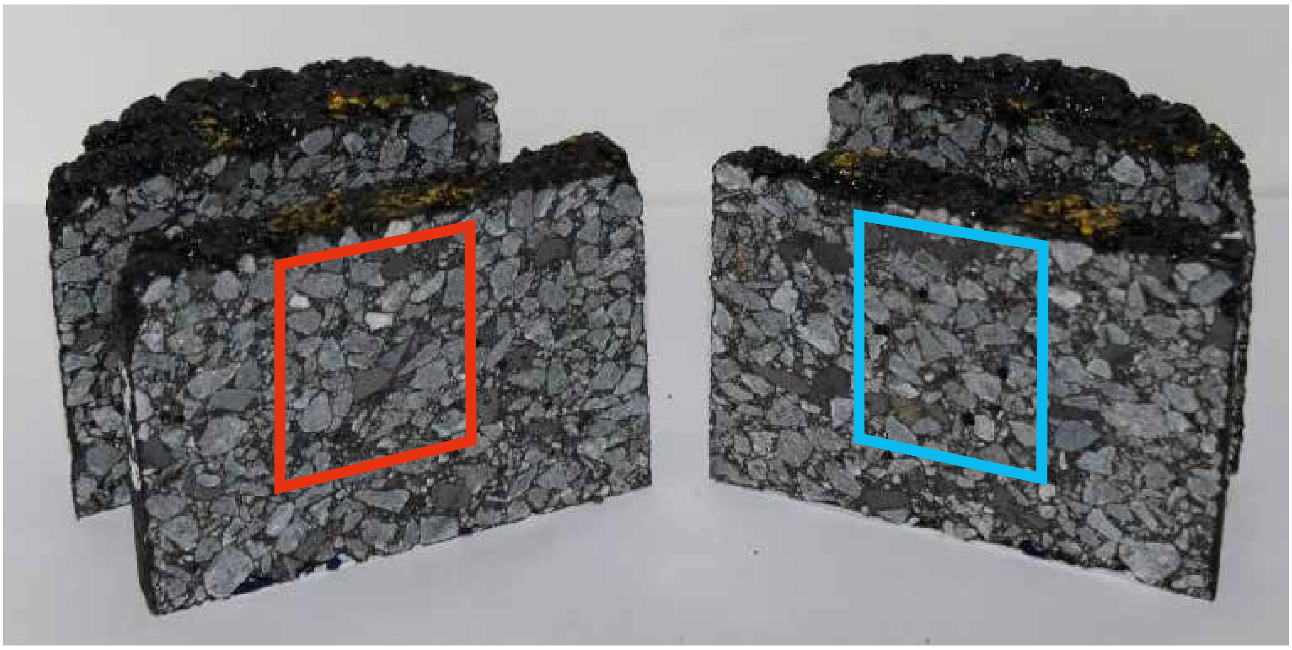


Figure 8.1:
Example of cutting thin sections from samples (normal asphalt concrete and not PERS).

Original size 1.69 x 2.56 mm shown with 25 times magnification

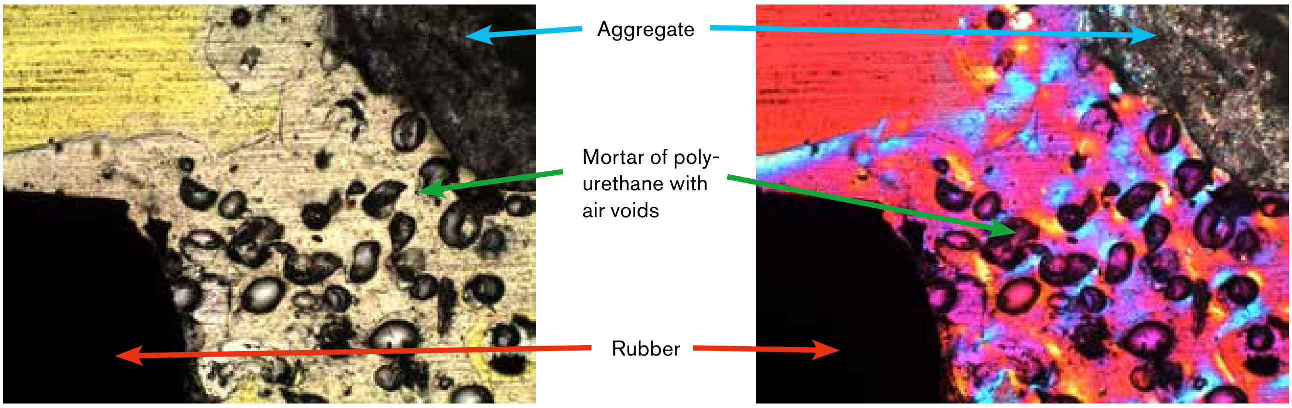


Figure 8.2:
Arnakke sample seen in the microscope with normal light.

Figure 8.3:
Arnakke sample seen in the microscope with UV light.

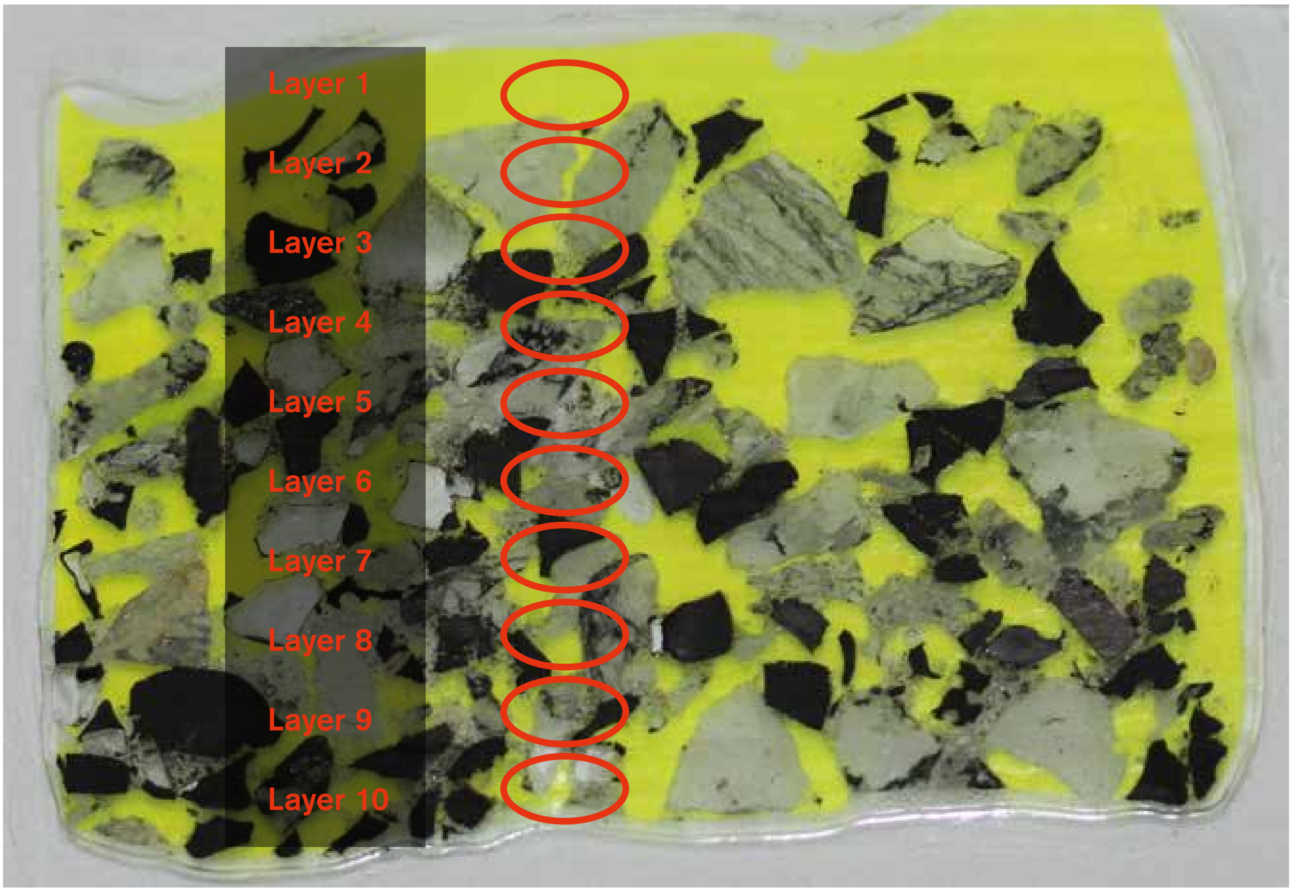
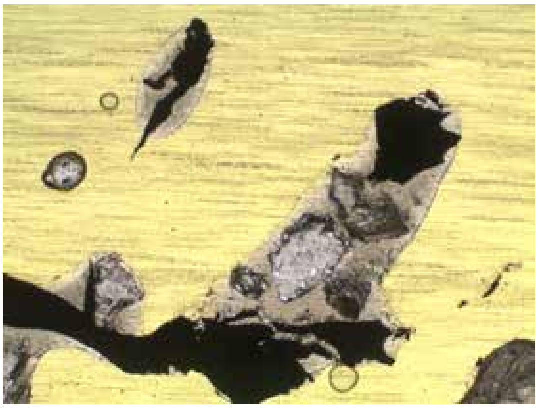
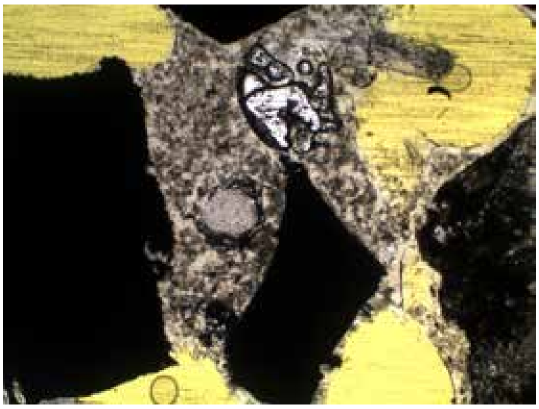
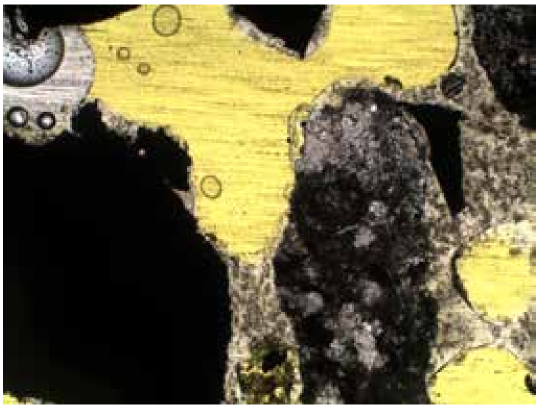
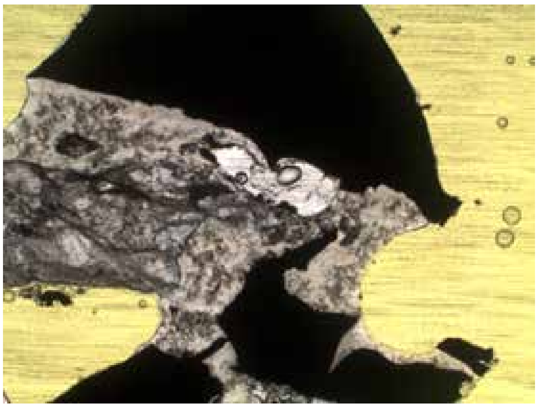
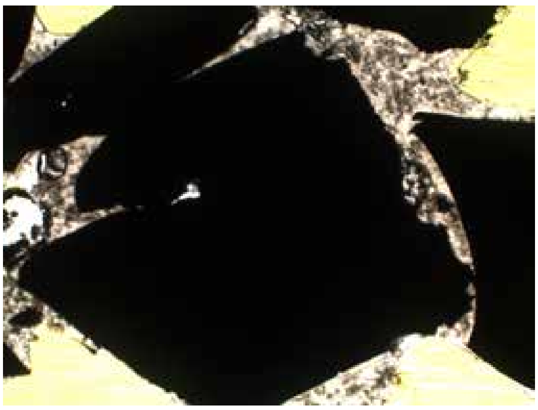
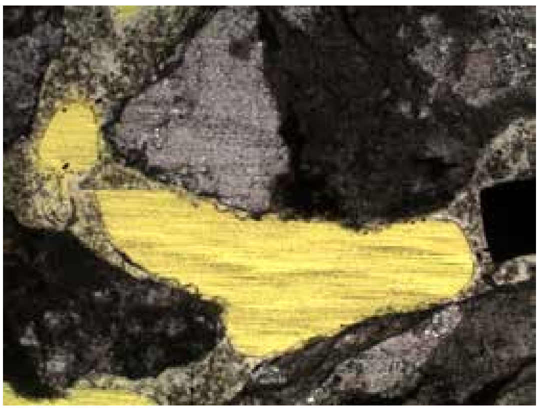


Figure 8.4:
Illustration of the 10 to 12 layers of a thin section of PERS where images have been taken for investigation. Every red area illustrates the position of a layer.

Layar	SV 13589 Kalvehave photo size 1.69 x 2.56 mm		Layer
1			5
2			6
3			7
4			8

Layar	SV 13589 Kalvehave photo size 1.69 x 2.56 mm	Layer
9		11
10		

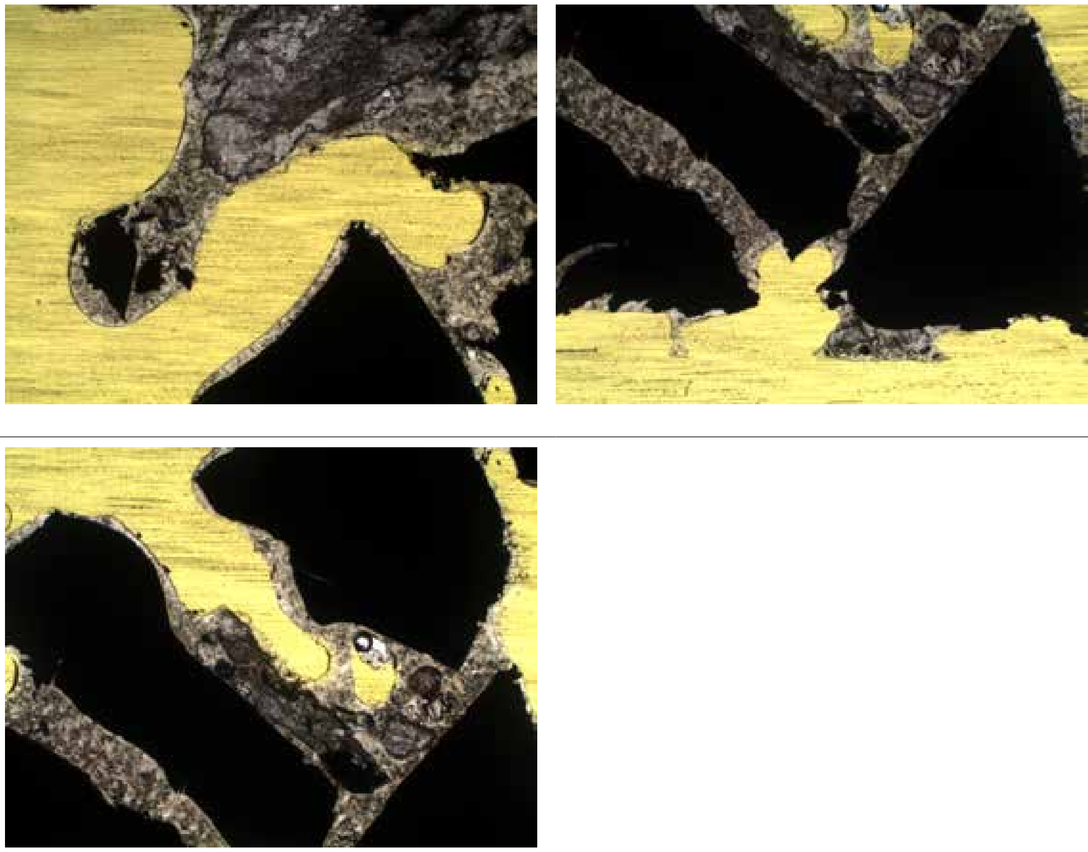
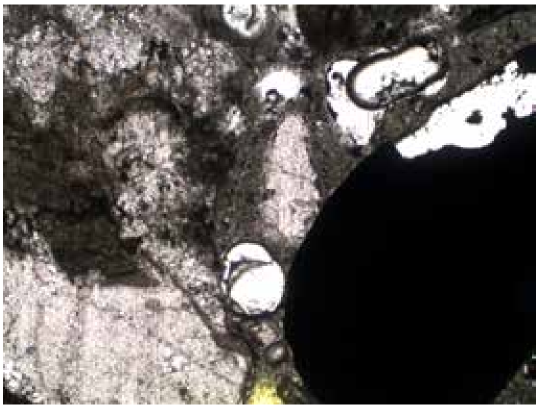
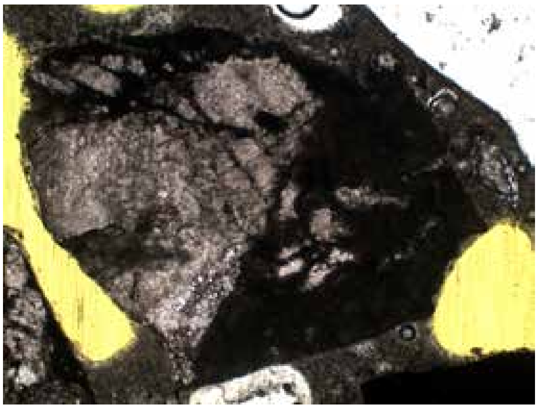
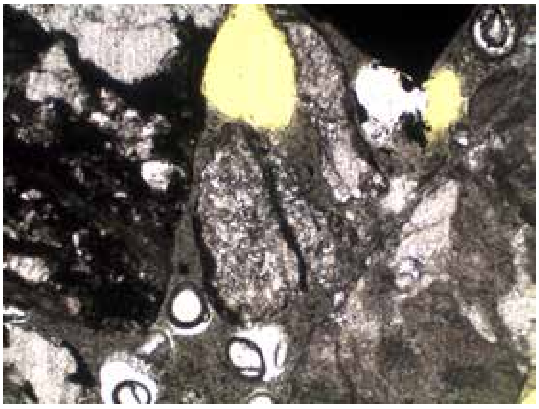
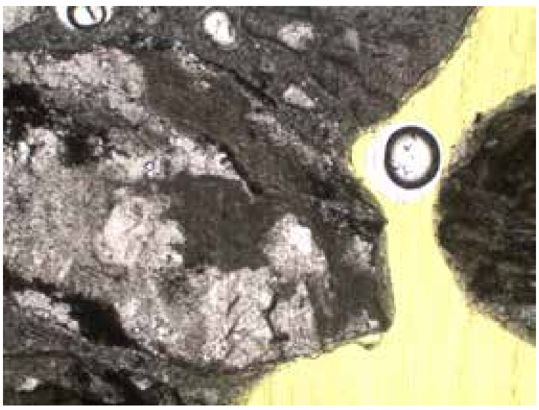


Figure 8.5:
Different layers of the Kalvehave test slab. Layer 1 is the pavement surface and layer 11 is the bottom layer. Original size of the samples on the images 1.69 x 2.56 mm shown with a magnification of around 25 times the original size.

The different layers of the Kalvehave test slab are shown in Figure 8.5. It can be seen that there is not so much polyurethane in the top layers and that the polyurethane present is generally situated under the stone and rubber aggregates and not coating the aggregates all way around. This will presumably cause a reduced strength of the material in the surface of the pavement. In the lower layers more polyurethane is present and the aggregates are coated with this material. There is a tendency of accumulation of polyurethane in the bottom layers. This can be explained by the polyurethane used in the Kalvehave mix had a low viscosity and ran off the top aggregates and accumulated in the bottom of the layers. This low viscosity was also observed during the laying process.

The different layers of the Sterrebeek test slab are shown in Figure 8.6. The polyurethane is evenly distributed down through all layers of the pavement and the polyurethane is coating the stone aggregates and rubber on all sides. Due to this the strength of the Sterrebeek slab must be considered better than the Kalvehave slab.

Layar	SV 13815 Sterrebeek photo size 1.69 x 2.56 mm		Layer
1			4
2			5
3			6

Layar — SV 13815 Sterrebeek photo size 1.69 x 2.56 mm — Layer

7 / 10

8 / 11

9 / 12

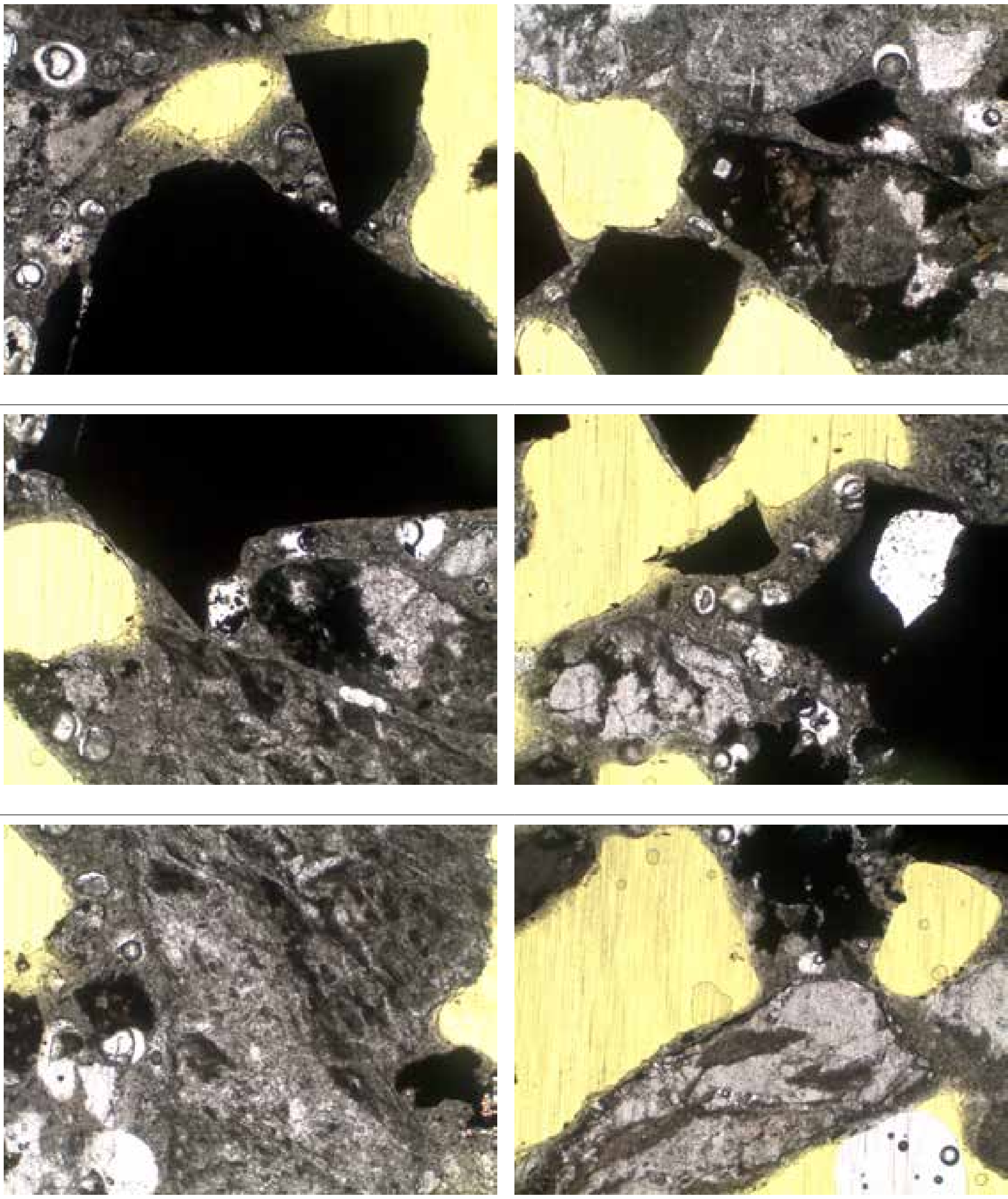
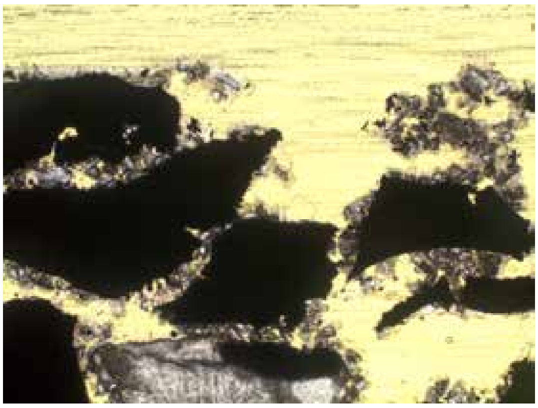
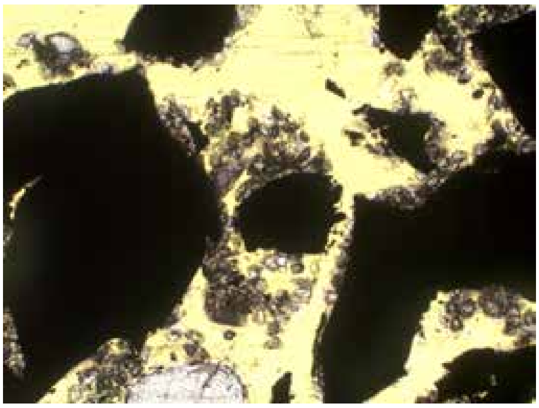
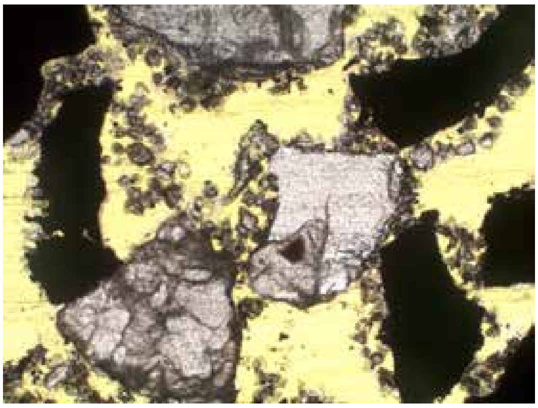
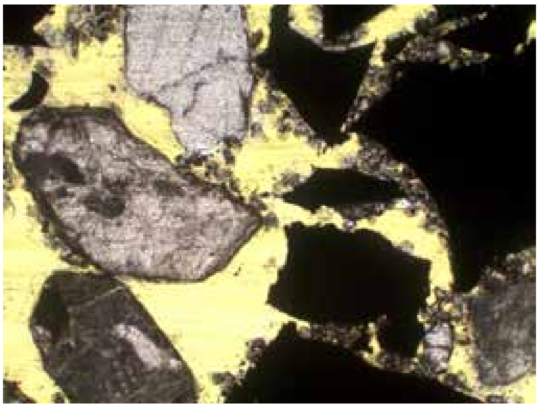
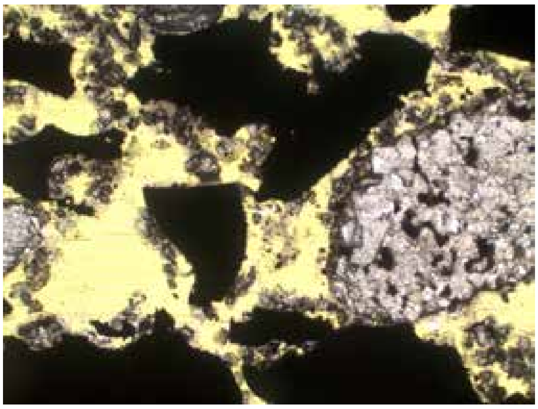
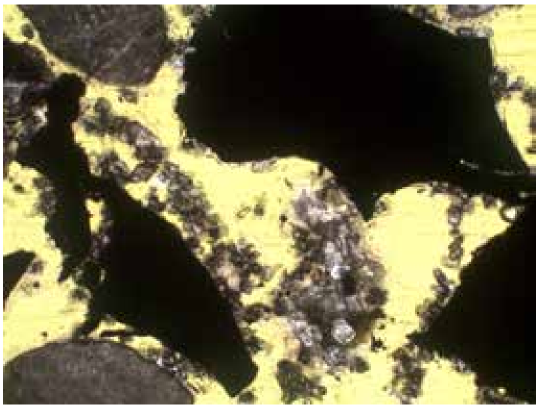
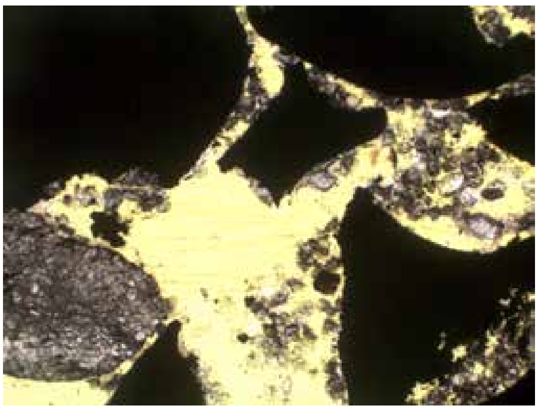
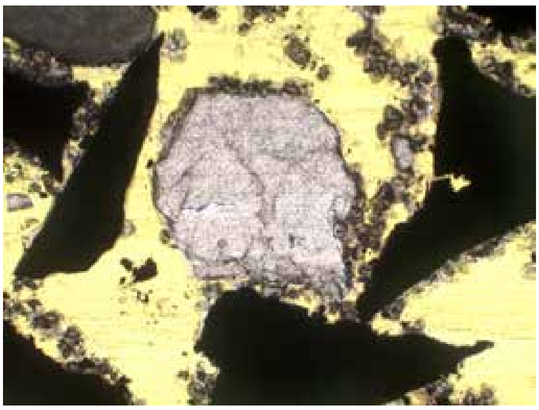


Figure 8.6:
Different layers of the Sterrebeek test slab. Layer 1 is the pavement surface and layer 12 is close to the bottom layer. Original size of the samples on the images 1.69 x 2.56 mm shown with a magnification of around 25 times the original size.

Layar	SV 13744 Nova Gorica photo size 1.69 x 2.56 mm		Layer
1			5
2			6
3			7
4			8

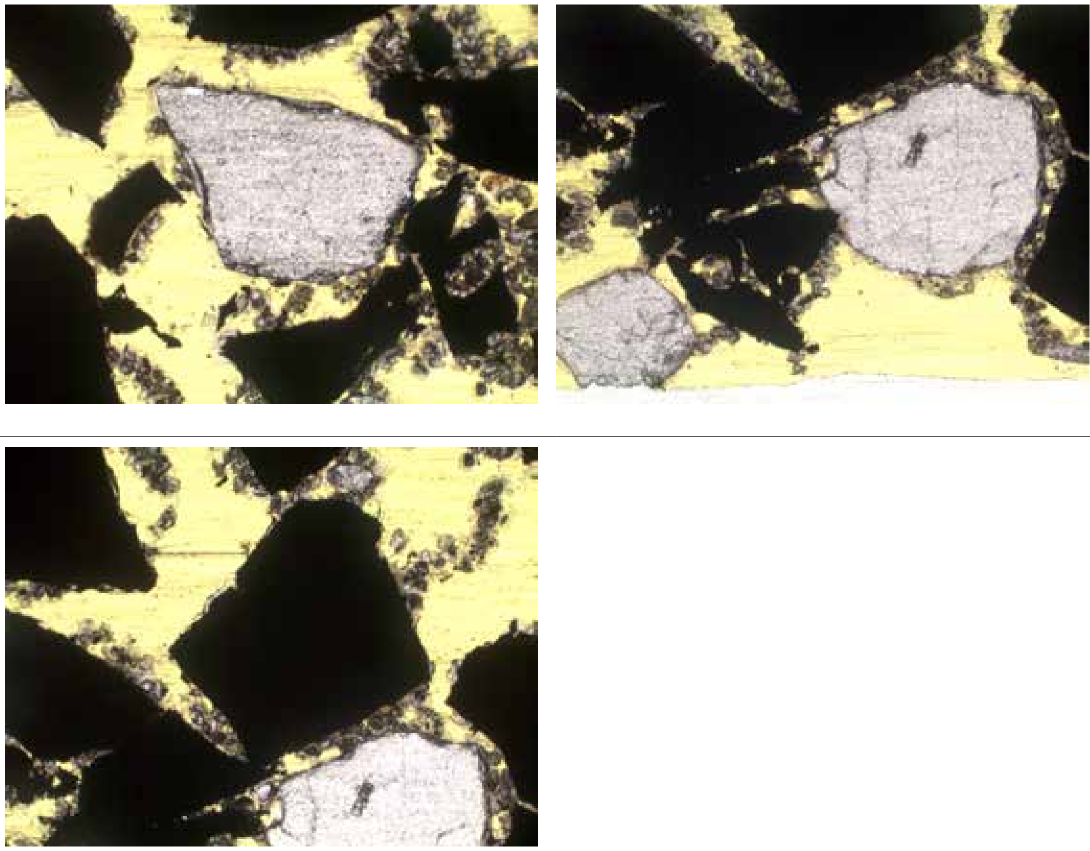
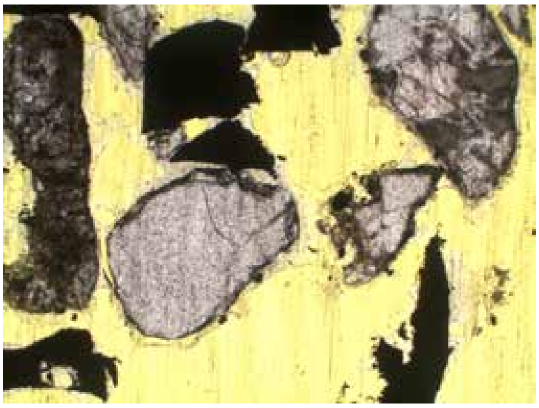
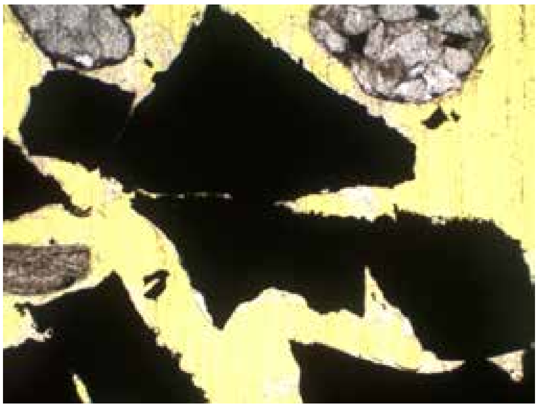
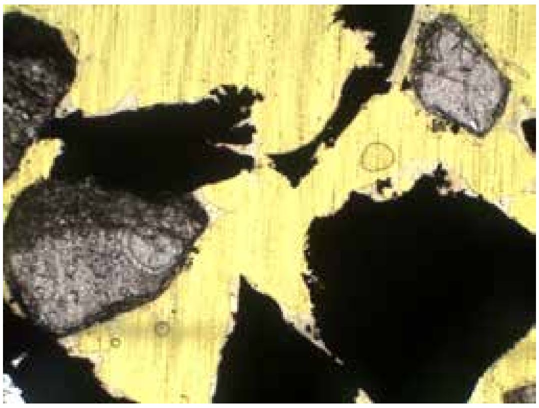
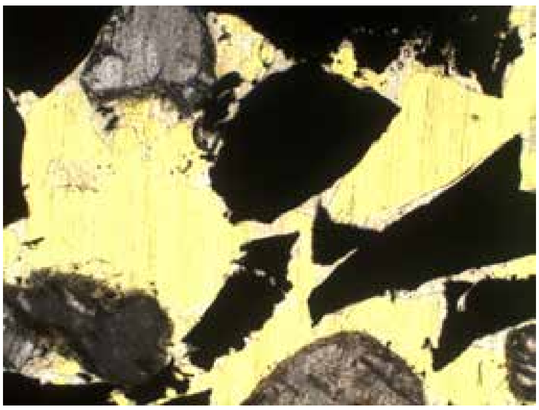
Layar	SV 13589 Kalvehave photo size 1.69 x 2.56 mm	Layer
9		11
10		

Figure 8.7:
Different layers of the Nova Gorica test slab. Layer 1 is the pavement surface and layer 11 is the bottom layer. Original size of the samples on the images 1.69 x 2.56 mm shown with a magnification of around 25 times the original size.

The different layers of the Nova Gorica test slab are shown in Figure 8.7. The aggregates are of a smaller size than used at the Kalvehave and Sterrebeek test slabs. A lot of dust can be observed at all layers. The polyurethane is evenly distributed down through all layers of the pavement. It seems that the dust attracts the polyurethane and the polyurethane accumulates on the small grains. Therefore the coating of the stone aggregates and rubber is not very good. This will presumably reduce the strength of these slabs.

The different layers of the Linköping test slab are shown in Figure 8.8. The polyurethane is evenly distributed down through all layers of the pavement. The thickness of the polyurethane film around the aggregates is very thin and hardly visible. The area of the polyurethane binding between the aggregates is quite small. This will presumably reduce the strength of these slabs.

Layar	SV 14001 Linköping photo size 1.69 x 2.56 mm		Layer
1			5
2			6
3			7
4			8

Layar	SV 14001 Linköping photo size 1.69 x 2.56 mm	Layer
9		11
10		

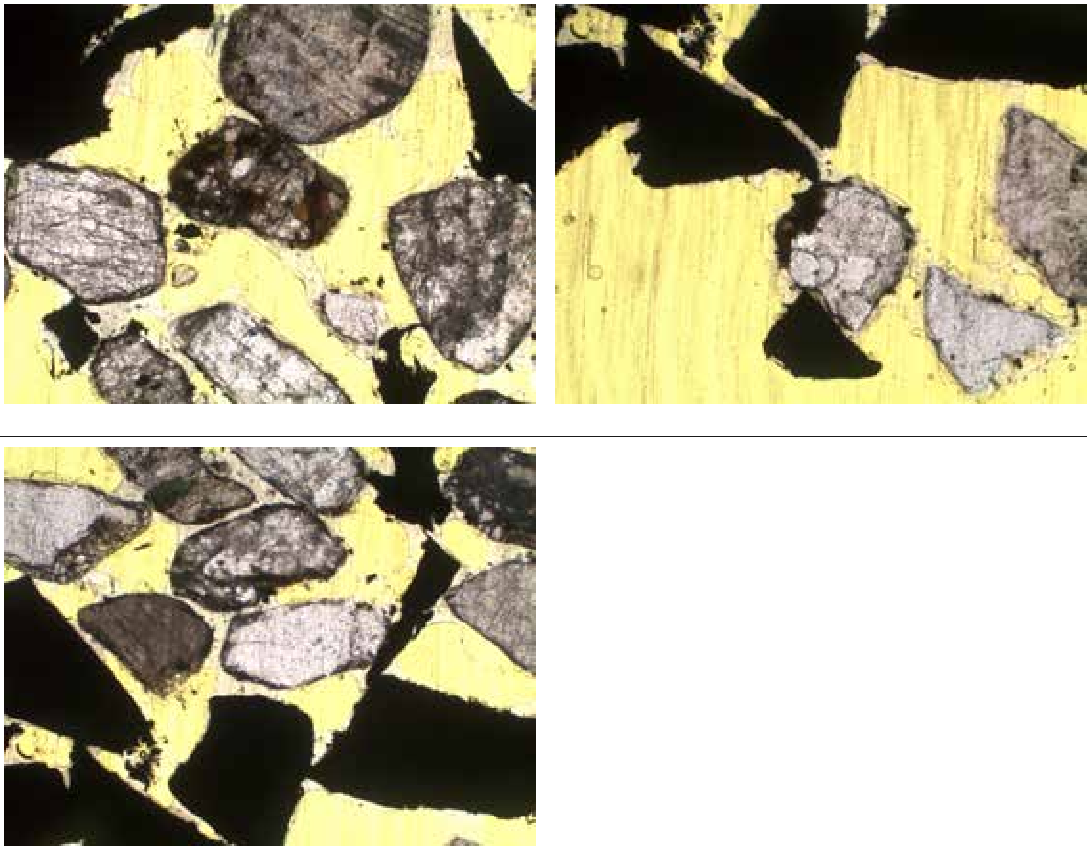


Figure 8.8:
Different layers of the Linköping test slab. Layer 1 is the pavement surface and layer 11 is the bottom layer. Original size of the samples on the images 1.69 x 2.56 mm shown with a magnification of around 25 times the original size.

The different layers of the Linköping test slab are shown in Figure 8.8. The polyurethane is evenly distributed down through all layers of the pavement. The thickness of the polyurethane film around the aggregates is very thin and hardly visible. The area of the polyurethane binding between the aggregates is quite small. This will presumably reduce the strength of these slabs.

9. Conclusion and discussion

Table 9.1:
Overview of the results of the measurements performed on the five test slabs.

Test Slab	Arnakke	Kalvehave	Nova Gorica	Linköping	Sterrebeek
Pendulum friction	45	57	64	63	62
Drainability [seconds]	5.0	19.0	-	22.0	3.2
Acoustical absorption max [Hz]	1000	630	800	1000	1000
Absorption coefficient [α]	0.95	0.48	0.61	0.72	0.92
Built in air void [%]	-	27.7	31.0	26.2	21.4
Surface texture MPD [mm]	0.79	0.67	-	0.31	0.80
Dynamic Young Modulus [MPa]	96	64	208	102	526

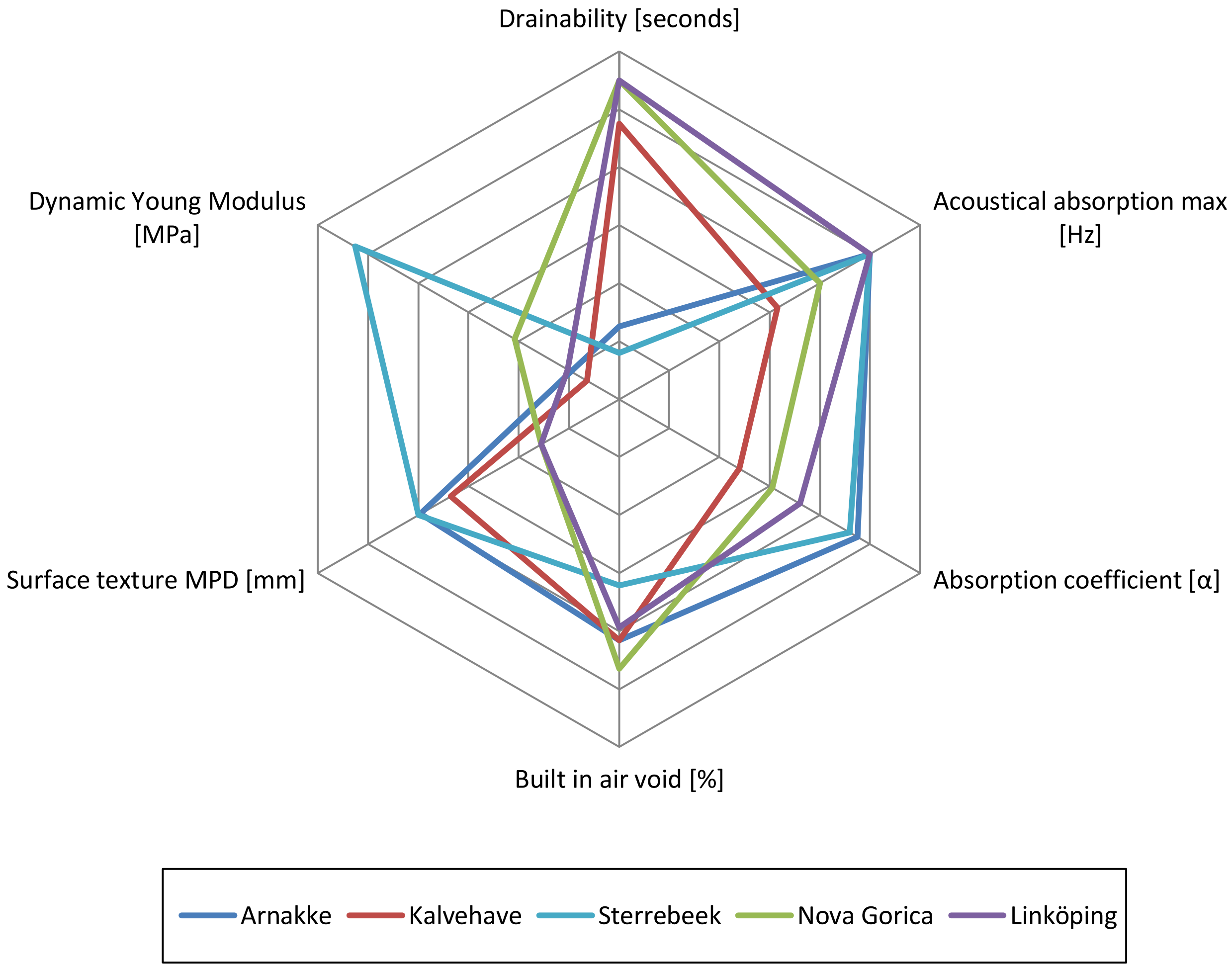


Figure 9.1:
Relative presentation of the measurement data modified so that all factors more or less are converted to a scale from 1 to 100.

All the 5 tested PERS test slabs are porous as well as elastic and by volume the aggregates are around 50 % stone material and 50 % rubber material. The binder used is polyurethane. The Nova Gorica and Linköping slabs have a maximum aggregate size of 3 mm and the three others have a maximum aggregate size of 5 mm. The test slabs were produced with different materials under different production conditions.

Table 9.1 gives an overview of all the measured results for the 5 PERS test slabs. To give a graphical representation of all the data related to noise emission (leaving out friction), Figure 9.1 gives a relative presentation of the same data modified so all factors more or less are converted to a scale from 1 to 100. To give a full representation of all 5 test slabs it has been assumed that Arnakke has the same built in air void as Kalvehave and that Nova Gorica has the same drainability and MPD as Linköping.

All the measured friction levels using the Pendulum method are at or higher than the old Danish 45 guideline. The Arnakke test slab has the lowest friction of 45. The friction of the two factory produced test slabs with small aggregates of 3 mm (Nova Gorica and Linköping) is the highest but followed closely by the test slabs from Kalvehave and Sterrebeek with larger aggregates of 5 mm.

The image evaluation of the thin and plane sections through the layers from pavement surface to the bottom gives some qualitative indications of the durability of the test slabs:

- The polyurethane used in the Kalvehave mix had a low viscosity and ran off the top aggregates and accumulated in the bottom layers. This might influence the durability of the slabs.

- For the Sterrebeek test slab the polyurethane is evenly distributed down through all layers of the pavement and the polyurethane is coating the stone aggregates and rubber on all sides. Due to this, the strength of the Sterrebeek slab must be considered better than the Kalvehave slab.

- A lot of dust can be observed at all layers of the Nova Gorica test. It seems that the dust attracts the polyurethane and the polyurethane accumulates on the small grains. Therefore the polyurethane coating of the stone and rubber aggregates is not very good. This will presumably reduce the strength of the slab.

- The polyurethane of the Linköping is evenly distributed down through all layers of the pavement. The thickness of the polyurethane film around the aggregates is very thin. The area of the polyurethane binding between the aggregates is quite small. This will presumably reduce the strength of these slabs.

The on-site produced slabs with 5 mm aggregates from Sterrebeek and Arnakke have very good drainability of 3.2 and 5.0 seconds comparable to new two-layer porous asphalt. The drainability of the Linköping test slab with the small 3 mm aggregates is 22 seconds and less good than the two slabs with 5 mm aggregates but still in a good state with high drainability. This might be caused by the smaller aggregates resulting in smaller dimensions of open communicating voids in the pavement.

Absorption spectrums from Sterrebeek and Arnakke are similar, with a high absorption coefficient of around 0.9 in the 1000 Hz band followed by the spectrum from Linköping with a lower absorption coefficient of 0.72. The spectre from Nova Gorica has a peak value in the 800 Hz band with an absorption coefficient of 0.61. The spectre from Kalvehave has a peak in the 630 Hz band, with the lowest absorption coefficient of 0.48. The design goal was to get the maximum absorption between 600 and 1000 Hz and this goal has been reached for all the test pavements according to these absorption measurements on cores from the test slabs.

The target air void for the PERS mix has been estimated to be 30 %. Generally the air void is quite high and around the target level for the Kalvehave, Nova Gorica and Linköping test slabs and a less for the Sterrebeek test slab.

The MPD of Arnakke and Sterrebeek test slabs are of the same magnitude of around 0.8 mm, Kalvehave a little lower at 0.67 mm, and Linköping significant lower at 0.31 mm. For the macro texture, the goal has been to get a high texture level at the short wavelengths and a low texture level at the longer wavelengths. This has been achieved for the test slabs.

The mechanical impedance expressed as the dynamic Young modulus (E) in increasing order is 64 MPa for Kalvehave test site, 96 MPa for Arnakke test site, 102 MPa for Linköping samples, 208 MPa for Nova Gorica samples and 526 MPa for Sterrebeek sample. The ratio is about 8 between the softer and the stiffer PERS, while it would be between 30 and 250 if the PERS were compared to a very stiff Dense Asphalt Concrete (E≅ 15000 MPa).

The measured parameters influencing noise are presented again in Table 9.2. This leaves out the friction. The influence of the parameters in relation to getting a road pavement with a low tyre-road noise emission level has been marked with the following colours based on the professional judgement of the authors:

- Green -Very good
- Yellow – Good
- Red – Less good

Based on this evaluation the prefabricated test slabs with 3 mm aggregates from Linköping should have the best performance in relation to low tyre road noise emission together with the on-site produced Arnakke test slabs with 5 mm aggregates. This evaluation can be somewhat biased because it is based on measurements performed on two types of prefabricated test slabs (Nova Gorica and Linköbing) that can be considered produced under ideal conditions and three test slabs produced in moulds at the road side not securing optimal production conditions (Arnakke, Kalvehave and Sterrebeek).

Table 9.2:
The influence of the parameters in relation to getting a road pavement with a low tyre road noise emission level based on the professional judgement of the authors. Green – Very good, Yellow – Good and Red – Less good.

Test Slab	Arnakke	Kalvehave	Nova Gorica	Linköping	Sterrebeek
Drainability [seconds]	5.0	19.0	-	22.0	3.2
Acoustical absorption max [Hz]	1000	630	800	1000	1000
Absorption coefficient [α]	0.95	0.48	0.61	0.72	0.92
Built in air void [%]	-	27.7	31.0	26.2	21.4
Surface texture MPD [mm]	0.79	0.67	-	0.31	0.80
Dynamic Young Modulus [MPa]	96	64	208	102	526

References

1. **Olesen, Erik; Bendtsen, Hans; Jensen, Bjarne Bo (2012):** “First experiences constructing PERS”. Internal PERSUADE Report, 2012.

2. **Bendtsen, Hans; Olesen, Erik; Pigasse, Gilles; Andersen, Bent; Raaberg, Jørn; Kalman, Bjørn; Cesbron, Julien (2013):** “Measurements at the Arnakke test site with small PERS sections”. PERSUADE report 2013.

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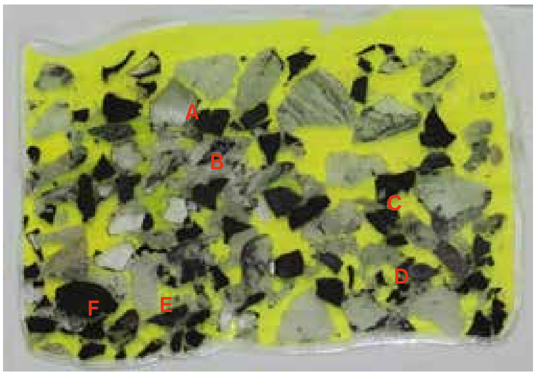
Annex A:
Thin sections from Arnakke

Thin section with position A - F

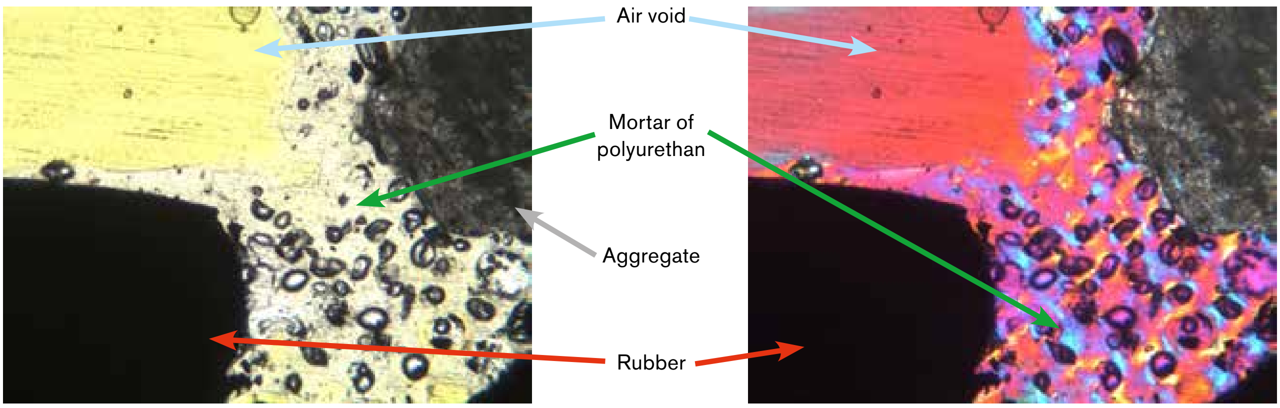


PERS from Arnakke Nord
Oktober 2011
SV 11377

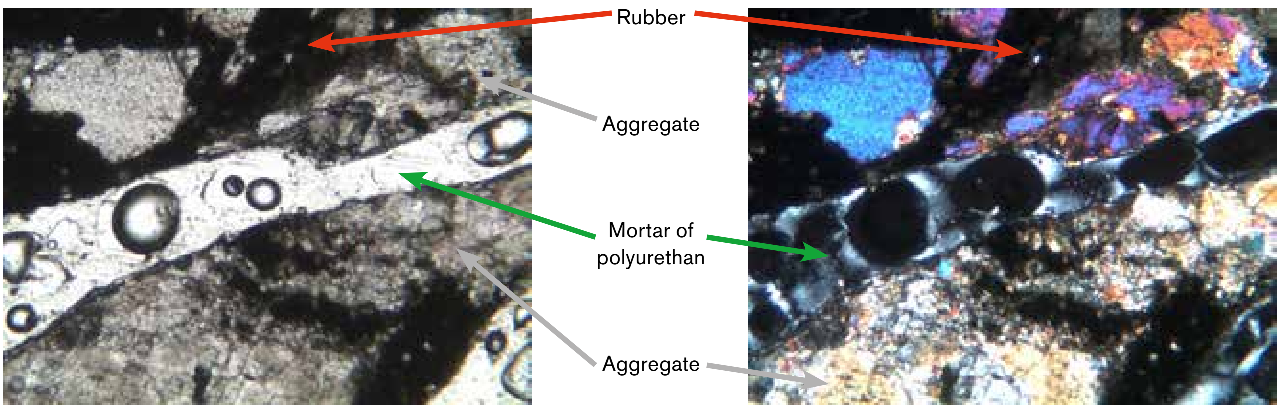
Thickness off the thin section is app.90 μy.

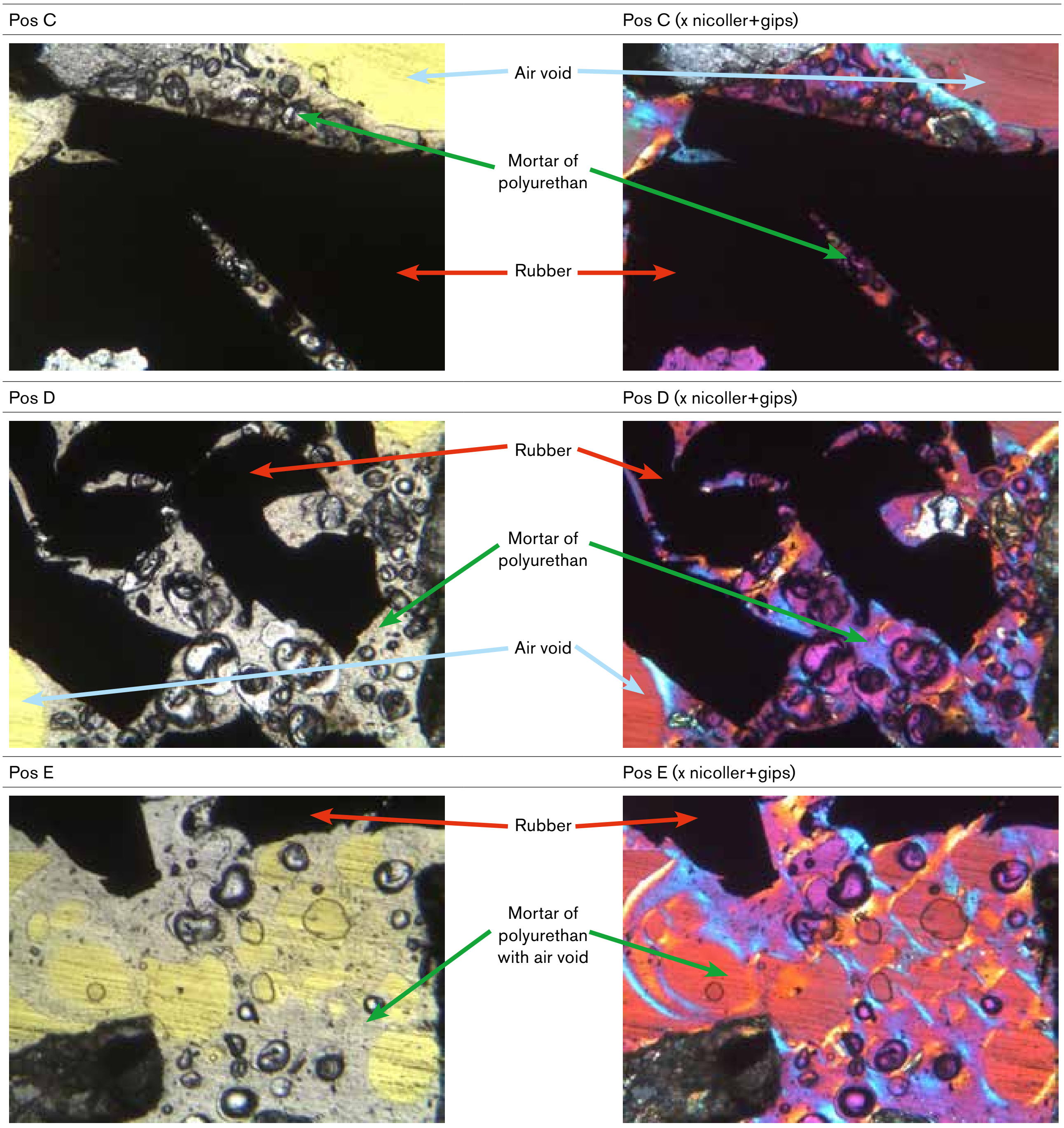
25x / 1,69 x 2,56 mm

Pos A | Pos A (x nicoller+gips)

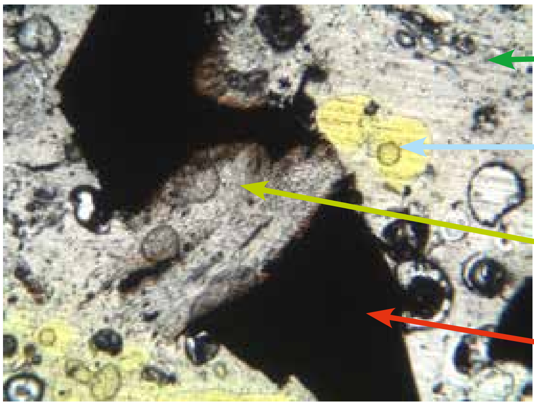


Pos B | Pos B (x nicoller+gips)

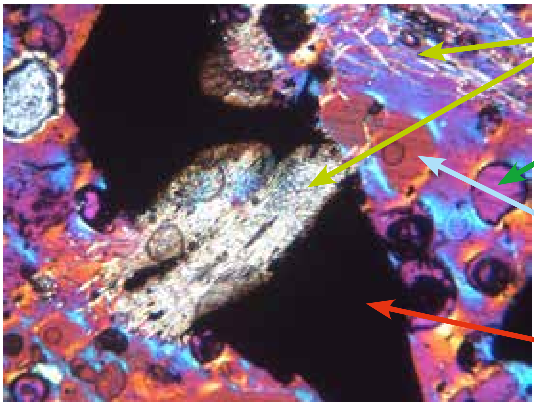



Pos C
Pos C (x nicoller+gips)
Air void
Mortar of polyurethan
Rubber
Pos D
Pos D (x nicoller+gips)
Rubber
Mortar of polyurethan
Air void
Pos E
Pos E (x nicoller+gips)
Rubber
Mortar of polyurethan with air void

Pos F	Pos F (x nicoller)

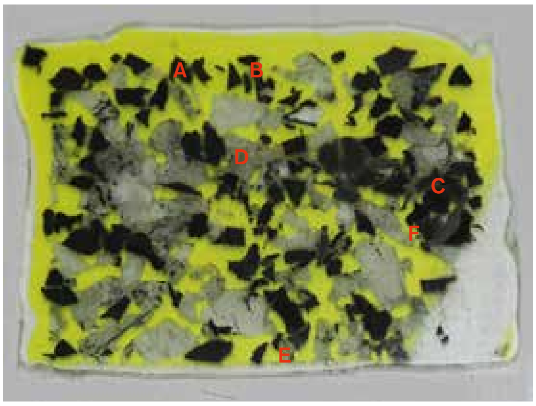


Pos F (x nicoller+gips)



Annex B:
Thin sections from Kalvehave

Thin section with position A - F

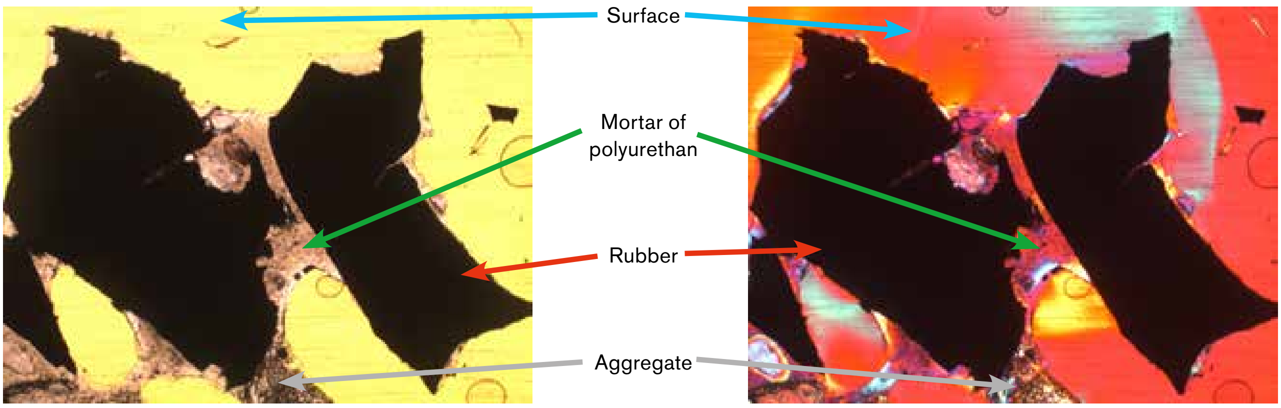


PERS from Kalvehave
August 2013
SV 13589-I

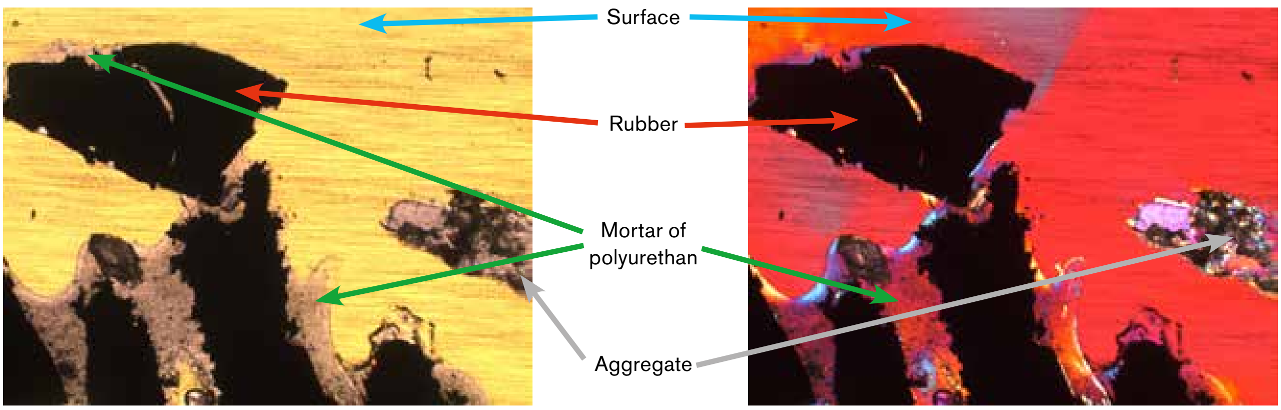
Thickness off the thin section is app.90 μy.

25x / 1,69 x 2,56 mm

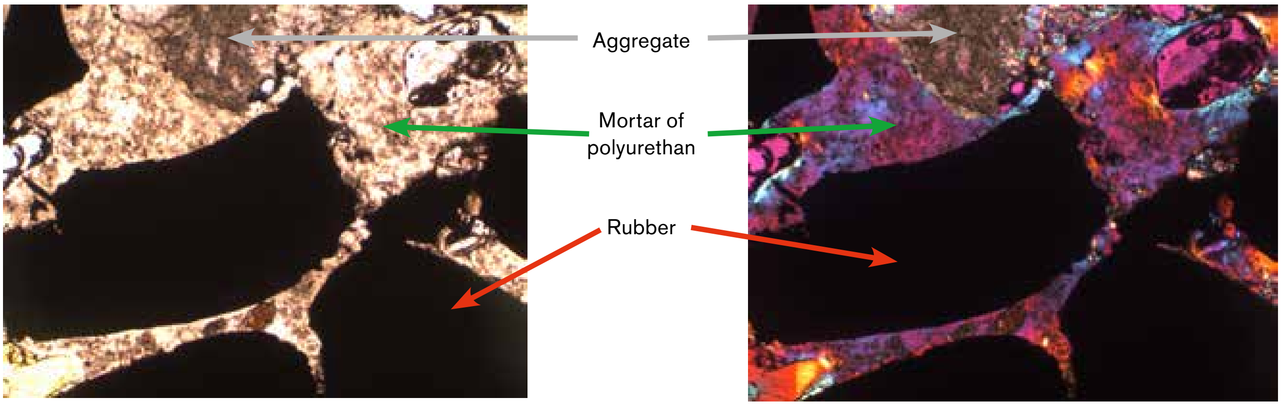
Pos A | Pos A (x nicoller+gips)



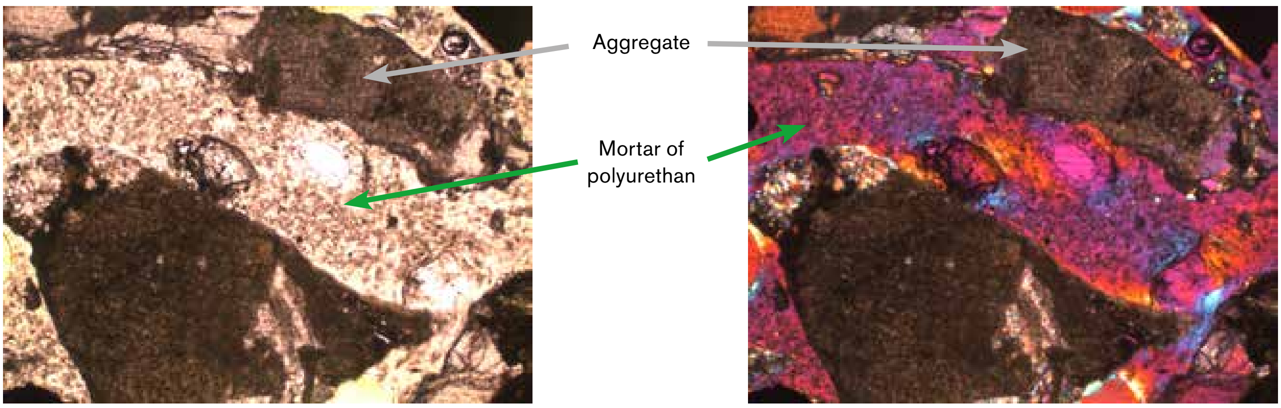
Pos B | Pos B (x nicoller+gips)



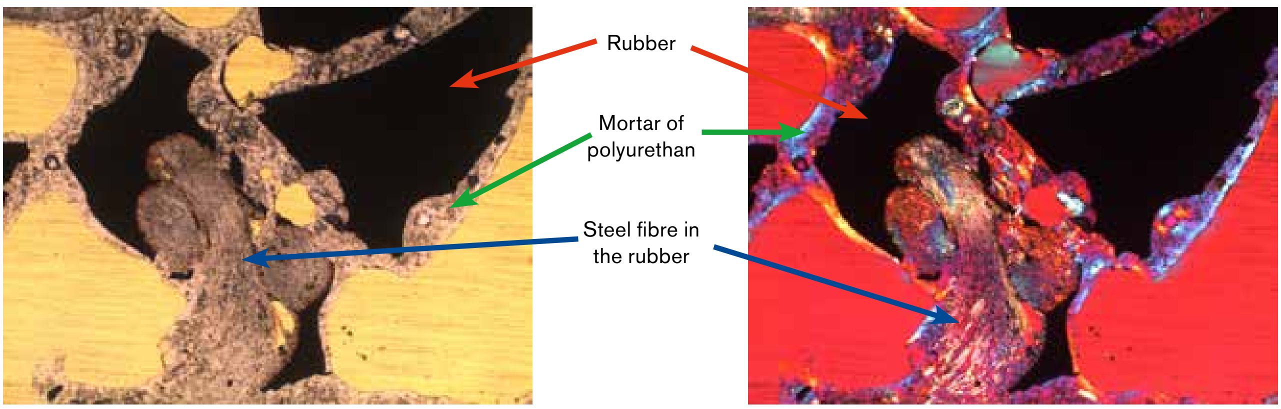
Pos C | Pos C (x nicoller+gips)



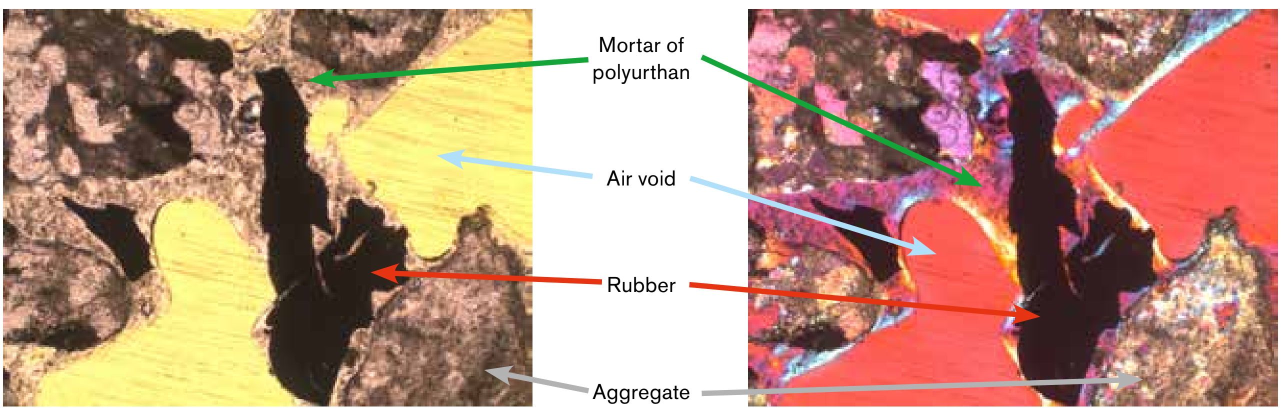
Pos D | Pos D (x nicoller+gips)



Pos E | Pos E (x nicoller+gips)

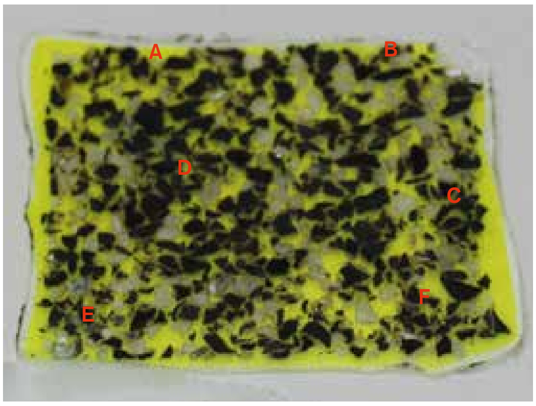


Pos F | Pos F (x nicoller+gips)



Annex C:
Thin sections from Nova Gorica

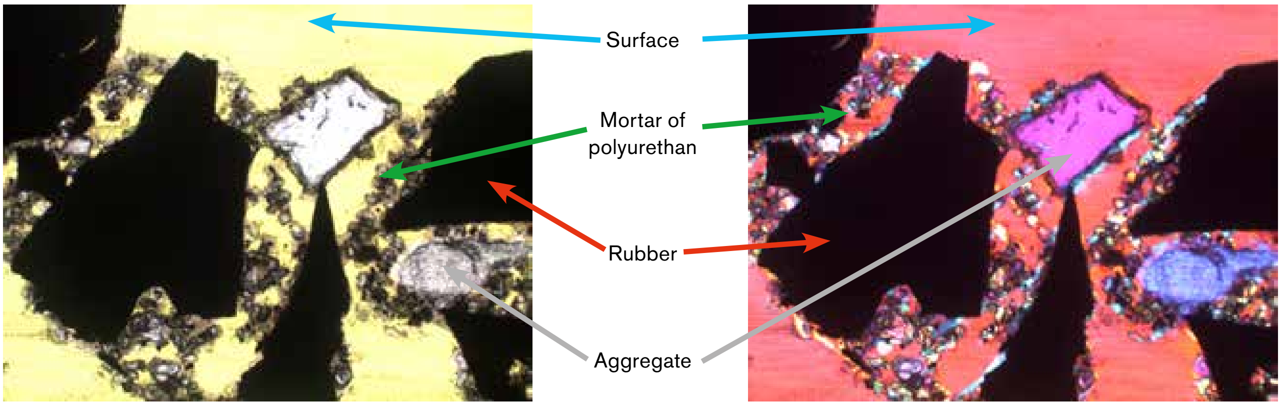
Thin section with position A - F



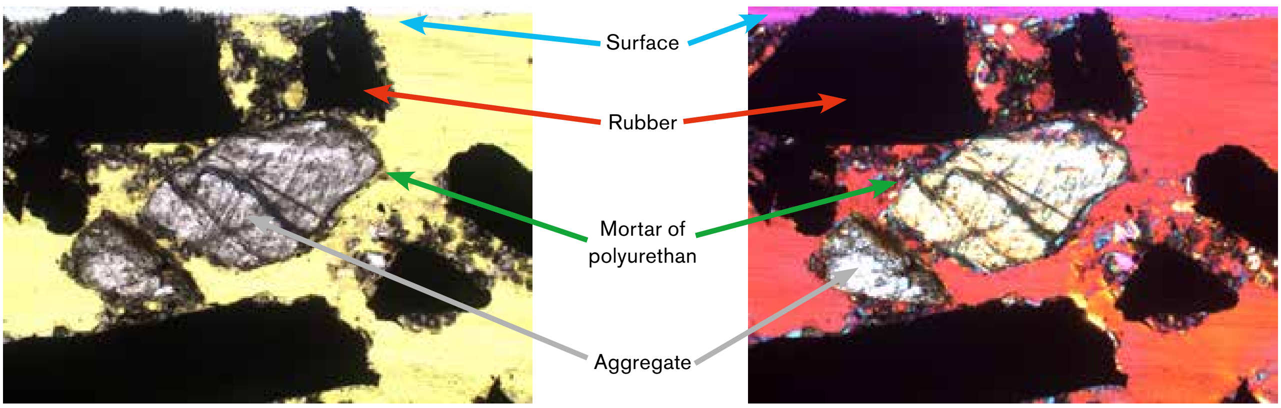
PERS from NOVA GORICA
November 2013.
SV 13744

Thickness off the thin section is app.90 my
25x / 1,69 x 2,56 mm

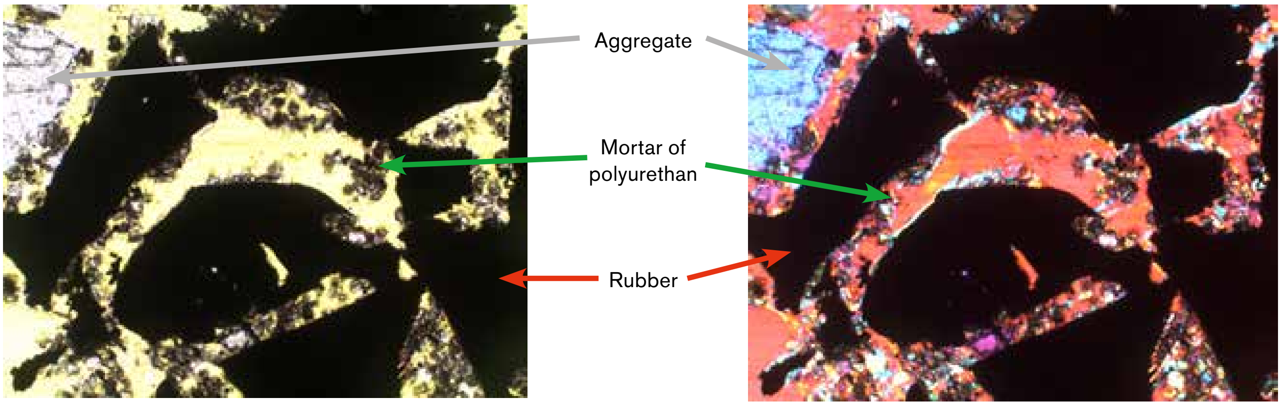
Pos A | Pos A (x nicoller+gips)



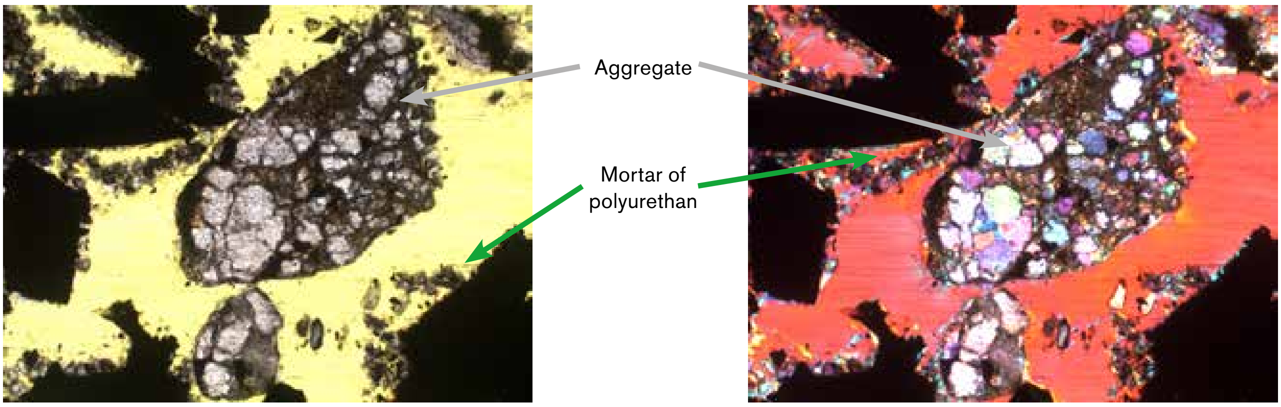
Pos B | Pos B (x nicoller+gips)



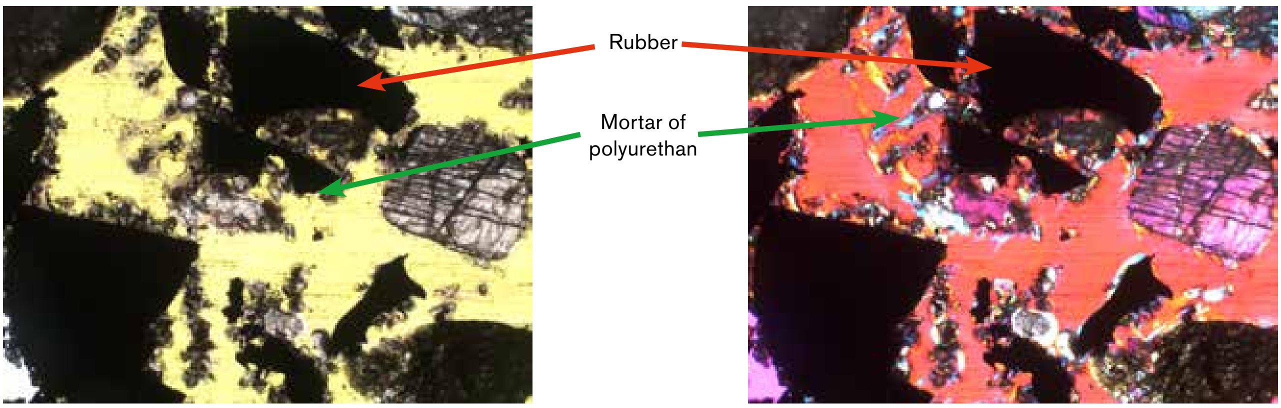
Pos C | Pos C (x nicoller+gips)



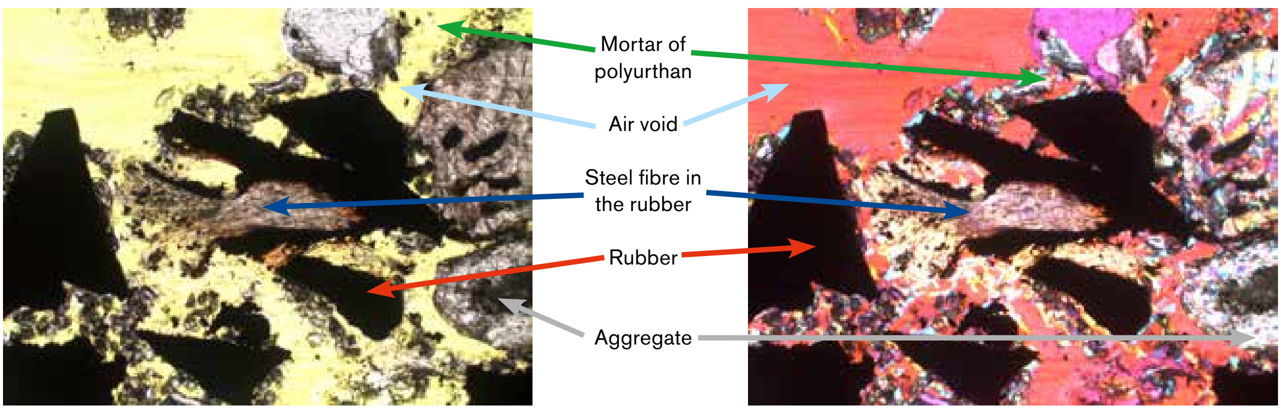
Pos D | Pos D (x nicoller+gips)



Pos E | Pos E (x nicoller+gips)

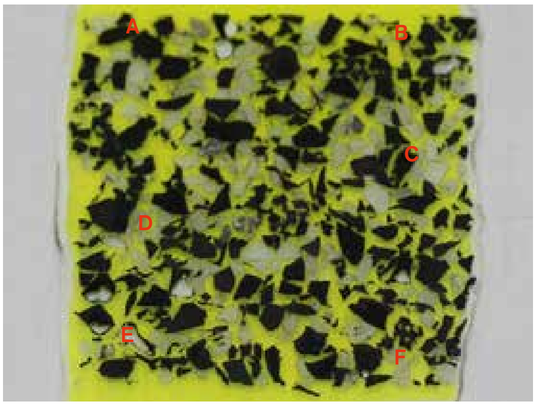


Pos F | Pos F (x nicoller+gips)



Annex D:
Thin sections from Linköping

Thin section with position A - F

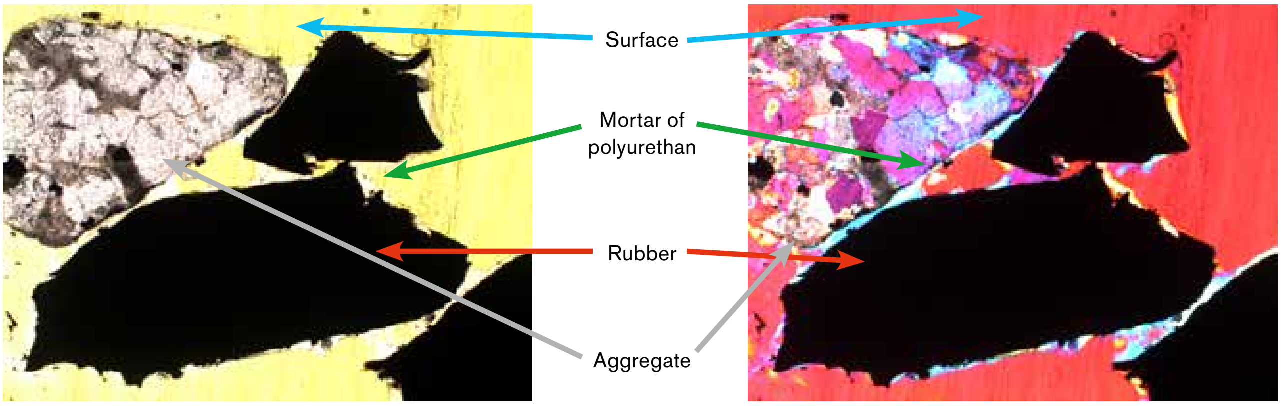


PERS sample from Linköping,
January 2014
SV 14001 - I

Thickness off the thin section is app.90 my.
25x / 1,69 x 2,56 mm

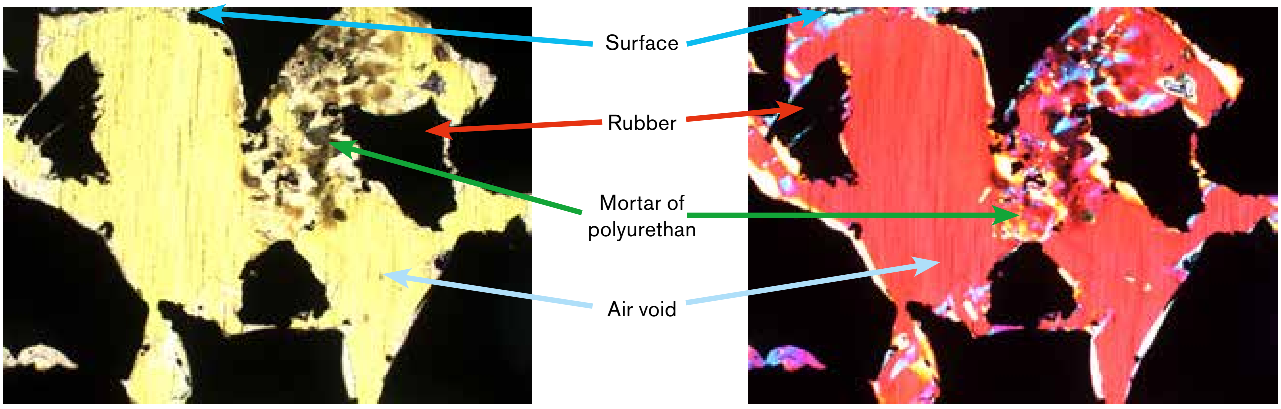
Pos A

Pos A (x nicoller+gips)

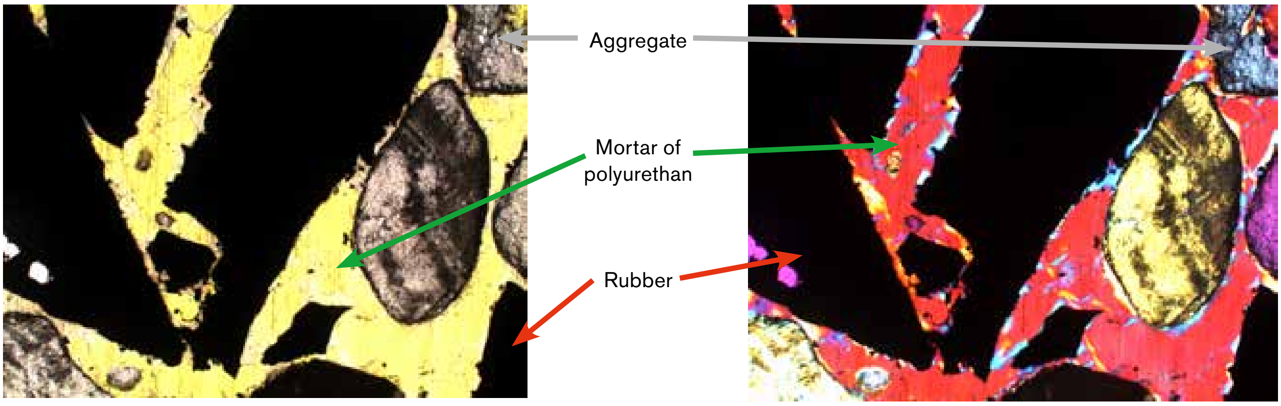


Pos B

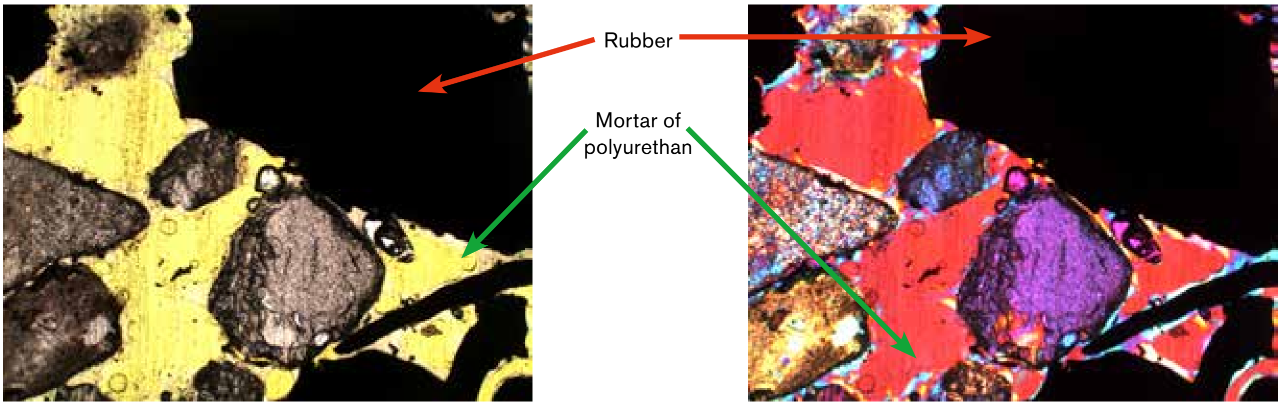
Pos B (x nicoller+gips)



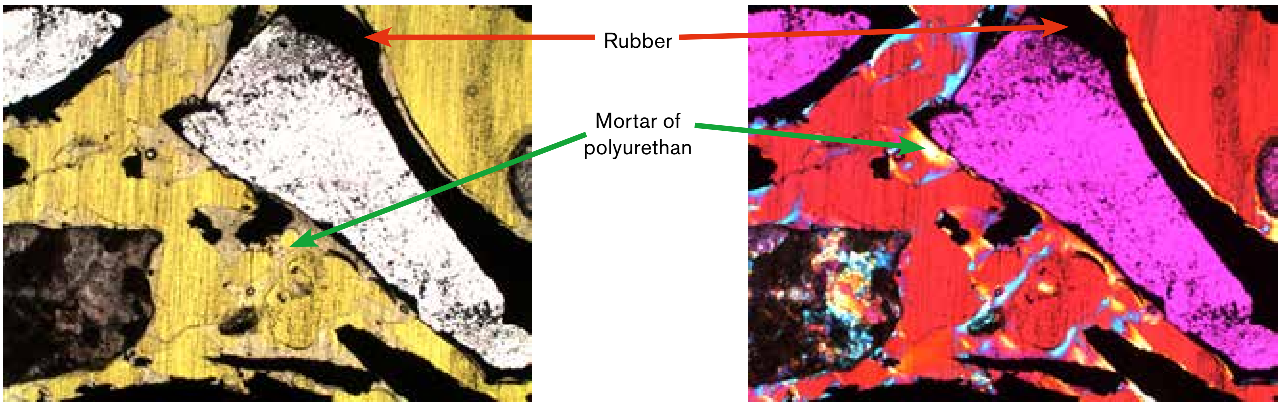
Pos C | Pos C (x nicoller+gips)



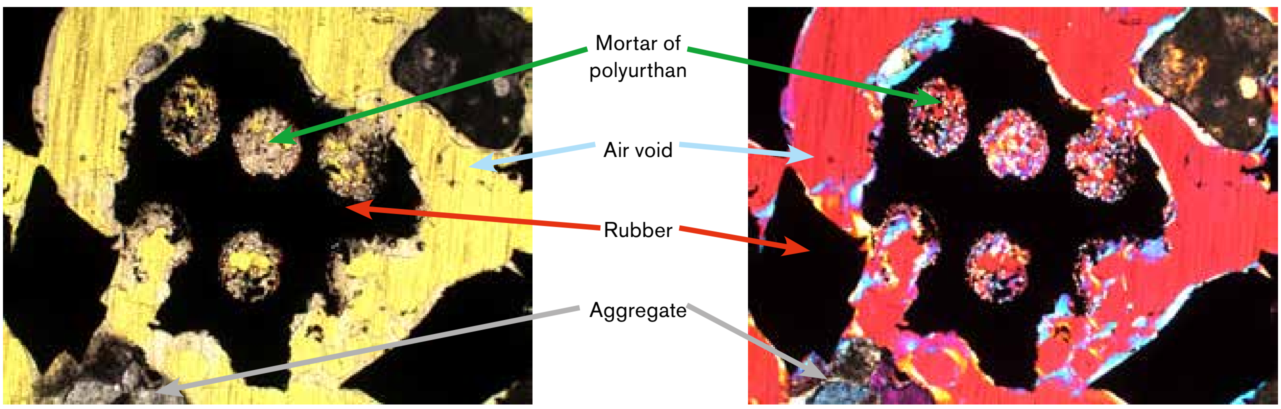
Pos D | Pos D (x nicoller+gips)



Pos E | Pos E (x nicoller+gips)

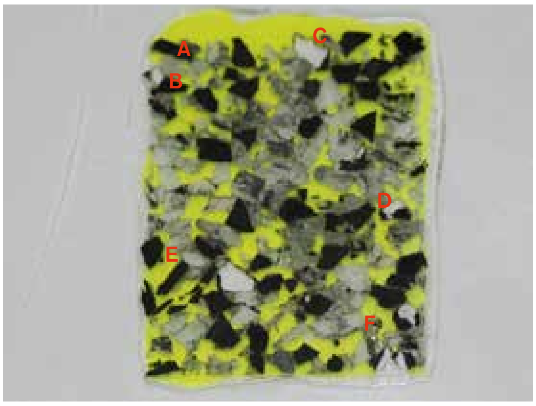


Pos F | Pos F (x nicoller+gips)



Annex E:
Thin sections from Sterrebeek

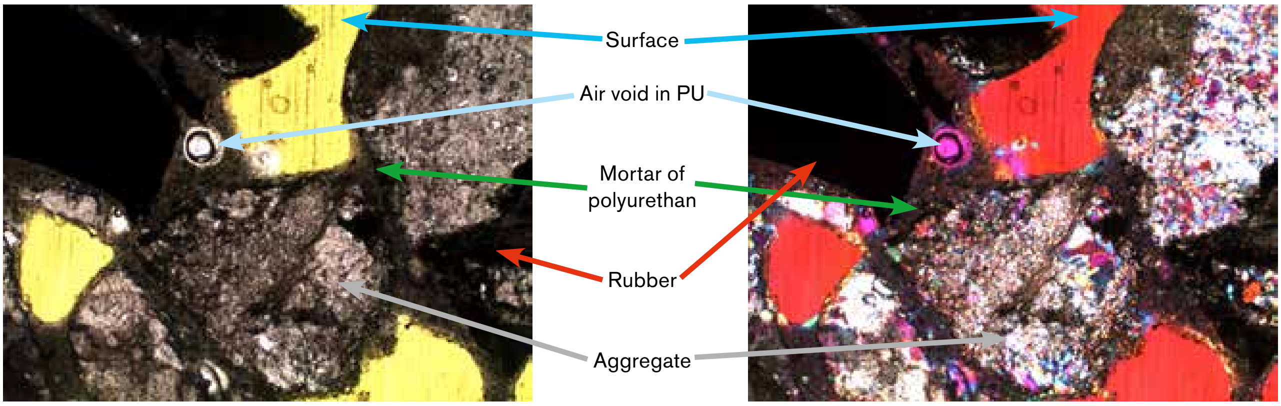
Thin section with position A - F



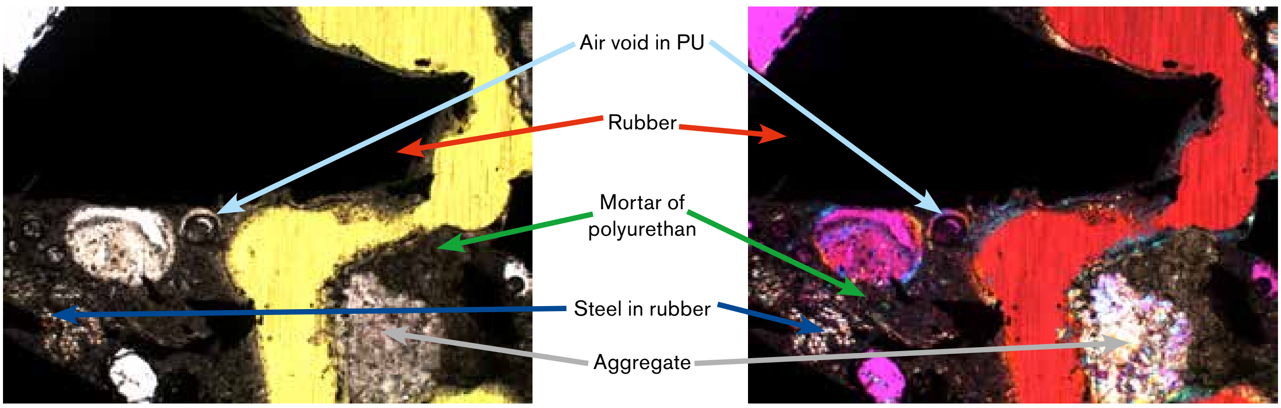
PERS sample from Sterrebeek,
December 2013
SV 13815-I

Thickness off the thin section is app.90 my
25x / 1,69 x 2,56 mm

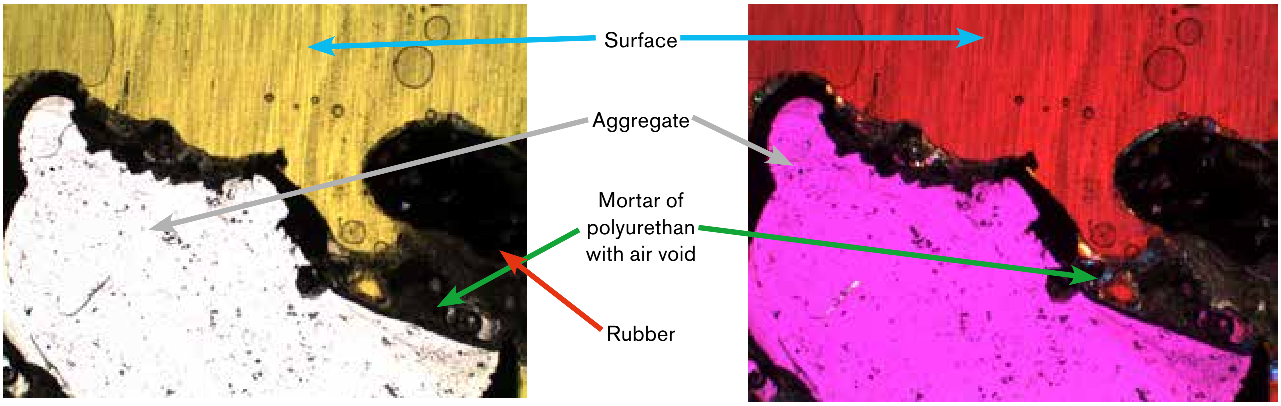
Pos A | Pos A (x nicoller+gips)



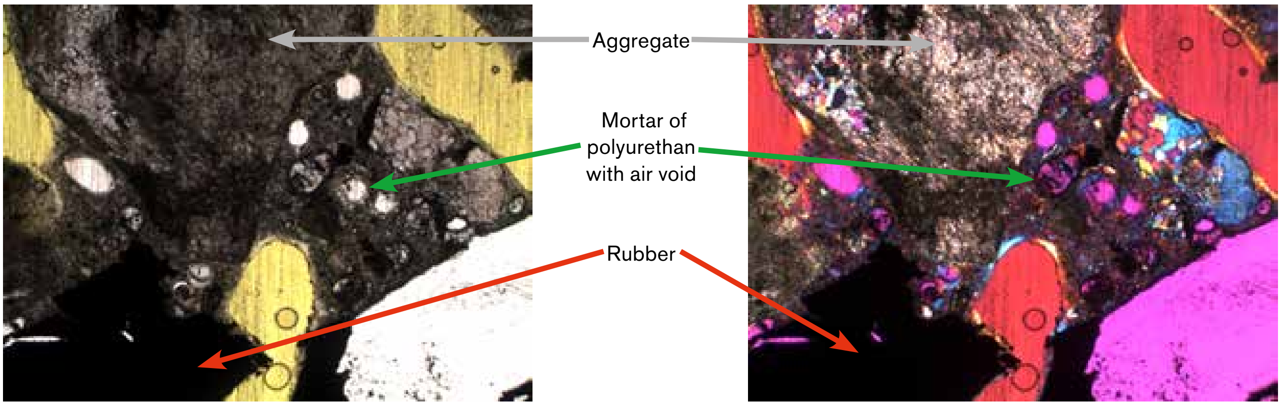
Pos B | Pos B (x nicoller+gips)



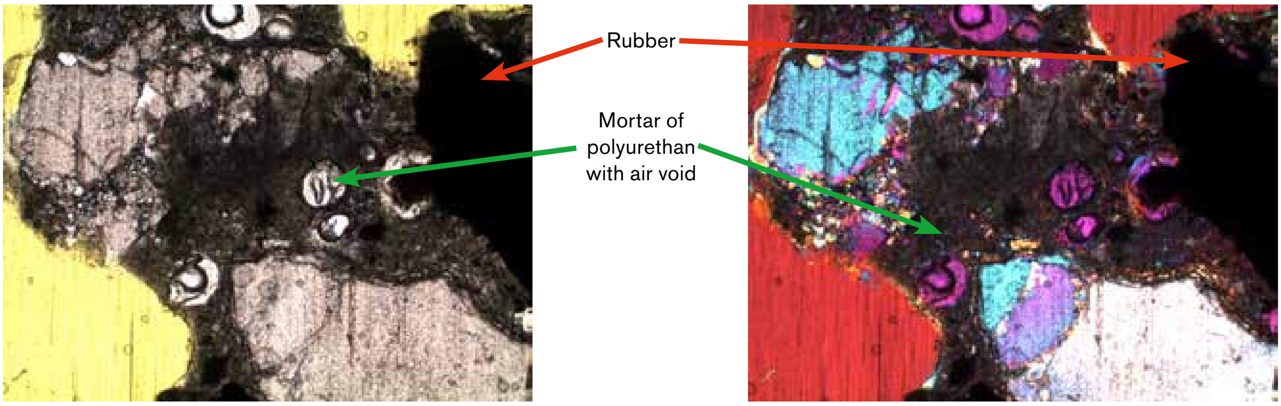
Pos C | Pos C (x nicoller+gips)



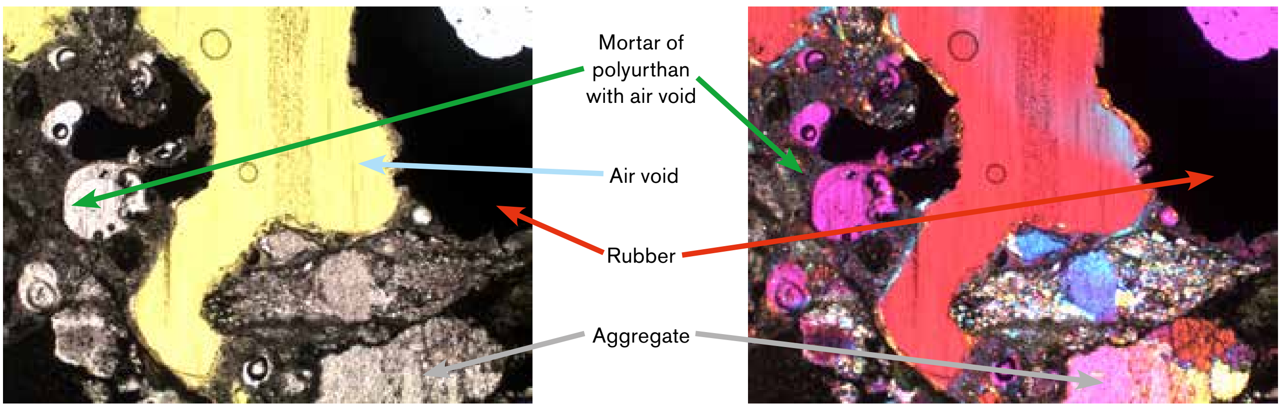
Pos D | Pos D (x nicoller+gips)



Pos E | Pos E (x nicoller+gips)



Pos F | Pos F (x nicoller+gips)



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Næstved og Skanderborg
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