Paving Porous Asphalt under sub-zero conditions

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ABSTRACT

The average service life of Porous Asphalt (PA) in the Netherlands is about 12 years. Due to the sea climate the winters are normally quite mild, but the last 2 winters the temperatures were significant lower than usual. As a consequence of this more frost damage occurred in predominantly old PA road sections. Frost damage caused premature raveling and potholes. The potholes were repaired with cold or mastic asphalt, but road sections with severe raveling in PA couldn't be repaired immediately because of the long frost period. The Dutch regulations don't allow laying PA under 5ºC. Because of safety reasons on some locations the total raveled PA layer was milled and traffic had to drive temporarily with a speed limitation on milled asphalt until the temperatures were suitable enough to lay new PA again. In other urgent cases the PA was temporary replaced under sub-zero temperatures, but had to be replaced again after some months because of premature raveling. Those two solutions have a negative effect on the mobility and give extra costs.
To avoid these problems Rijkswaterstaat gave two contractors the opportunity to replace PA on two test sites on motorway A58 near Breda under sub-zero temperatures. The goal of these test sections, laid in the night from 19 to 20 Ferbuary 2010, was to realise the same PA quality as PA laid under normal weather conditions. In this paper the production and laying process as well as the results of the field and laboratory tests are discussed.

Keywords: Porous Asphalt, Rejuvenators, Repair method, Compaction, Durability, Low temperature

1. INTRODUCTION

The Netherlands is a crowded country (401,4 inhabitants/km² in 2011) with an extended motorway network (3270 km). Due to that a lot of people live near the motorways and suffer from traffic noise, which can lead to stress and diseases. That is the reason why the Dutch government decided in 1990 to lay only noise reducing surfacings such as Porous Asphalt (PA) as a standard wearing course for motorways. The layer thickness of PA, with a maximum grain size of 16 mm and a minimum design void content of 20%, is 50 mm. The average service life of Porous Asphalt in the Netherlands is about 12 years. Due to the sea climate the winters are normally quite gentle, but the last winters the temperatures were significant lower than normal. As a consequence of this more frost damage occurred, mostly in old PA road sections which were already planned to be maintained. Frost damage caused premature raveling, potholes and widening of longitudinal joints. The potholes were repaired with cold or mastic asphalt, but road sections with severe raveling couldn't be repaired immediately, because of the long period of too low temperatures. The Dutch National Standard for Contracts in Civil Engineering Works [1] provides for requirements for processing a PA layer only when air temperature (t in °C) complies with $t \geq w+5$, where w denotes wind velocity in m/s. Lower laying temperatures may result in poor PA quality, because of the following. As a consequence of the cold binder layer the bonding of PA will be poor and due to faster cooling down of PA, a sufficient compaction becomes critically.
If the road owner is confronted with severe raveling of a PA road section during a long frost period, he could choose until then between the two following options:

- mill carriageway wide the total raveled PA layer and let the traffic drive temporarily on milled asphalt with a speed limitation until the temperatures are suitable again to lay new PA
- replace the raveled PA road section under sub-zero temperatures (temporary solution) and replace this definitely after some months.

Those two solutions have a negative effect on the mobility and result in extra costs.
To find a solution for this Rijkswaterstaat challenged the Dutch contractors and selected two of them to replace PA on two test sites on motorway A58 near Breda under sub-zero temperatures. The goal of these test sections was to realise the same PA quality as PA laid under normal weather conditions. In this paper the production and laying process as well as the results of the field and laboratory test are discussed.

2. CAUSES OF FROST DAMAGE IN POROUS ASPHALT

The Netherlands has a soft sea climate, but statistically once in ten years a severe winter can occur. Due to the severe winters of 2008/2009 and 2009/2010, with lots of snowfall, long periods with sub-zero circumstances followed by freeze/thaw periods, the service life of some PA road sections was shorter than usual as a consequence of frost damage. This frost damage in PA occurred mostly in road sections with old PA which already was planned to be maintained the next year. The cause of the premature raveling [2] was that the bitumen in PA is strongly aged due to the high void content of 20%. Aged bitumen is brittle and becomes even more brittle at lower temperatures. Due to traffic loading in winter time micro cracks will arise and will grow further if they are filled with condensed water that expands during freeze/thaw cycles. The cracks will grow further until stones get loose from the surface. If one stone has disappeared, more stones easily will follow because a lack of support. The frost damage will cause extreme raveling, lots of potholes and opening of longitudinal and transversal joints.

3. TEST PROGRAM

In the following sub chapters will be discussed how the laying process was monitored and how the quality of PA was determined with in situ measurements and laboratory tests. Each contractor got the opportunity to lay a 300 m long lane wide test section on the left lane of motorway A58 near Breda (2 lanes per carriageway) to proof that PA could be laid under sub-zero conditions with the same quality as laid under normal weather conditions. Because only one lane had to be laid, also the raveling process of the adjacent lane is followed in time because it is known that if one lane is maintained (inlay), especially at lower temperatures, it will mostly result in premature raveling of the adjacent lane. This is caused by the following processes or a combinations of:
- fast milling process, which can initiate cracks in the old PA layer
- driving of rollers over the old brittle PA, which causes micro cracks in the bonding bridges between the stones of the old PA
- spilling of loose fresh PA material on the old PA. The coarse stones can fill the voids in PA, which can result in

cracks caused to traffic loading.

3.1 Monitoring the laying process

To monitor the test site conditions and processes of the two contractors, the Process Quality Improvement (PQi) method was used. The PQi method was developed in the ASPARi network and refined by [3]. The aim of the PQi method is the improvement of Process Quality by closely monitoring PA construction work and making operational behaviour explicit. The data is made visually available in graphs and animation to the paving crews afterwards, so that they can observe their operational process, discuss and analyse the results and propose improvements to their work methods and operational strategies.

A typical PQi cycle ideally consists of:

- *Preparation I* (in the week before measurement) - prepare instruments, organise resources, inform lab staff of the contractor, prepare machines for the mounting of instruments and power supply;
- *Preparation II* (before the operations start) - check site design, undertake site calibration, select location for base station, record site conditions, hold a preparatory meeting with the asphalt crew, instruct assistants, set up and start up off the instruments (before
- *Data collection* - temperature profiling, monitoring all asphalt pave machine movements, monitor weather conditions, nuclear density profiling and recording all noteworthy events;
- *Data analysis and visualisation* - download data from instruments, analyse all data and prepare visualisations and animations, write project report;
- *Feedback* session – discuss all results, visualisations and animations with the paving crew, laboratory technicians and others directly involved in the project.

The key instruments and parameters for monitoring (per contractor):

Task	**Instrument**	**Method**	**Accuracy & frequency**
Monitor weather conditions	Vantage Pro 2 weather station	Weather station set up next to the construction site to log local weather conditions	Ambient temperature, wind speed, relative humidity and solar radiation data logged at 5-min intervals
Measure asphalt surface temperature behind paver screed (back up for IR-Line scanner)	FLIR ThermaCAM	Infrared images taken manually	Every 5m behind the PA asphalt paver screed across the road surface from the side of the road
Measure asphalt surface temperature behind paver screed	Raytek Infrared linescanner	linescanner mounted on the back of the paver.	scans 256 temperature points on a line 40 cm behind the screed in 150 Hz.
Cooling Curve Calibration Unit: Measure surface temperature cooling rate and at the same spot Measure in-asphalt temperature cooling rate	handheld FLIR InfraCAM in comb with Voltcraft plus – channel thermometer	Cameras set up on tripods at 3 fixed positions approx. 250m apart; Thermo-coupler placed in the middle of asphalt layer	IR-Images taken manually every 30 seconds; In asphalt Temperature logged automatically every 30 seconds;; (2 CCCU's per section)
Monitor the movements of all asphalt paving machinery	GPS receivers on the paver and the rollers**	Base station set up on site & GPS receivers on paver and rollers.	Differential GPS accuracy of < 10 centimetres, Data logged at 1-sec intervals
Measure asphalt density	nuclear density gauges	Density measured after every roller pass at fixed temperature logging positions	location: cooling curve calibration unit
Record noteworthy incidents on site	Sony IC voice recorders	Record incidents as they occur	one per paver, and two for the measuring staff at each section
** one basestation (Trimble™); Trimble™ GPS receivers on equipment KWS; Topcon GPS receivers on equipment DuraVermeer.			

Based on the gathered data processing the following outputs are produced:

- The initial PA temperature progression in the form of 2D Temperature Contour Plots: and the progression of surface and core temperature during the cooling of the mix combined with nuclear density measurements (the Cooling Curve Calibration measurements);
- The paver's operational characteristics;
- Individual and overall compaction behaviour during construction in the form of Compaction Contour Plots;
- Indicators for the scatter in results and work methods;
- Vulnerable areas and issues (for future failure analysis);
- A 4D animation (3D with time as the fourth dimension) of the entire process in the ProPave animation tool;
- Recommendations for process improvement (after the feedback session).

The PQi also has indirect results. The data are captured in a dossier in which the operations and conditions are permanently geo referenced for future failure analysis. The PQi increases awareness of quality for all asphalt crew and improves communication within the team. For the contractor the PQi provides more insights into the differences between asphalt crews. In unison teams and firm can identify and select "best practice" to work towards more uniform work methods. Not to forget: Quality improvement and the limitation (reduction) of risks for the contractor.

3.2 Laboratory tests

To determine if the quality of PA laid under sub-zero conditions is the same as PA laid under normal weather conditions, cores were drilled to carry out the following tests:

- Indirect Tensile Strength Ratio according to NEN-EN-12697-12 to test the water sensitivity. The tests were carried out on drilled cores with a 100 mm diameter
- Rotating Surface Abrasion Test (RSAT) [4], see photo 1).

Normally the RSAT is carried out on slabs, but in this case it was more practical to compose a specimen from three cores with a diameter of 150 mm. A loaded steel wheel with a solid rubber tire drives back- and forward on the PA specimen, which is mounted on an axle which only can rotate in one direction. The test temperature is 20˚C. In order to simulate the shear loading of traffic, the direction of the axle varies a little from the direction of movement. To achieve this, the wheel was fixed in an angle of 33.7˚. To spread the abrasion force over a certain area the specimen rotates slowly, driven by the abrasion forces themselves. In the forward movement of the wheel the specimen is rotating with it and in the backward movement of the wheel the rotation of the specimen is blocked. In this stage the forces are at maximum. The resistance to raveling is expressed as the total amount of loose material after 24 hours of testing.

Photo 1: RSAT

- Cantabro test according to NEN-EN12697-17 at a test temperature of 18˚C. As test specimens 100 mm diameter drilled cores were used with a height of 50 mm.

3.3 Laser measurements

To determine if the laying process influences the increase of raveling of the freshly laid PA and of the adjacent old PA lane, laser measurements were carried out directly after laying and 6 and respectively 28 weeks after laying with the Automatic Road Analyser (ARAN).

Photo 2: Aran with laser.

4. CONSTRUCTION OF THE TEST SECTIONS A58

In December 2009 contractors were challenged to come up with ideas to address the topic of paving under sub-zero conditions without loss of quality. In this bidding procedure the costs of constructing the test section were only one of the judged items. The quality of the porous asphalt, the feasibility of the idea, the pace of construction, the reaction time, the environmental aspects and safety in general were more important. Two contractors were selected for constructing the test sections, Dura Vermeer and KWS Infra. The location of the test sections was on the left lane on motorway A58 near Breda. The length of the test sections was 300 m each, width of 4,50 m on average. In between approximately 300 m was left open in order to make it able for transport movements without hindering each other. The PA mixture, which should be laid was a socalled PA+. This is the current standard PA in the Netherlands and contains 5,2% bitumen 70/100 in the mix and a drainage inhibitor. On Wednesday 17th of February 2010 Rijkswaterstaat gave the starting signal that the test section should be constructed in the night of Friday 19th of February.

In order to be able to pave under sub-zero conditions without loss of quality the process was analysed and critical parameters were addressed:

- production and transport
- bonding / tack coat
- paving and compacting
- prevention of damage of adjacent PA
- protection of workers and equipment

Normally in winter time the asphalt mixing plants are closed because there is no demand of asphalt. In this period maintenance is carried out. Both contractors had to select and start up one of their mixing plants. At the asphalt mixing plant only simple precautions were taken to prevent pipes and mechanical parts to get frozen. During transport at sub-zero conditions loss of temperature can not be avoided. But increasing production temperature was not the right answer because the PA with high void content and increased binder content is sensitive for dripping despite the drainage inhibitor. The solution was to select trucks with highest grade of insulation characteristics. One contractor on purpose chose a centrally located mixing plant with driving time of two hours instead of the closest one. In this way he wanted to prove that in future sub-zero situations, when mixing plants are normally closed, production can take place in one centrally located mixing plant. In this particular case the time from production and loading of the truck to the unloading in the paver on the A58 was even three hours. The drop in temperature in this situation was only 10 ºC! So it was proven that production in one central mixing plant and transport in isolated trucks makes it possible to reach almost every location in The Netherlands with an acceptable slight drop in temperature of the asphalt mixture.

At sub-zero conditions spraying the tack coat consisting of bitumen emulsion can result into problems. At these low temperatures the breaking of the bitumen emulsion can not be controlled and takes longer time. At sub-zero conditions the sprayed tack coat can get frozen. To control the process of spraying and breaking of the tack coat, both contractors used a paver with an integrated spray bar, see photos 3 and 4. A polymer modified bitumen emulsion was applied.

Photo 3: Paver with integrated spray bar.

Photo 4: Detail of spray bar

One contractor additionally preheated the milled surface in front of the paver to increase temperature of the surface. A mobile jet engine, The Surface Jet, was used as can be seen on photo 5.

Photo 5: SurfaceJet

Apart from the paver with integrated spray bar, paving and compacting was conducted with standard equipment. A continuous supply of asphalt was organised and paving was at constant speed and joint heaters were used. The main difference with paving under normal conditions is that the time in which the asphalt mixture must reach its density is shortened dramatically. The time frame for compacting this PA+ mixture with a void content of 20% and a layer thickness of 50 mm under sub-zero conditions is approximately 20 minutes. Therefore the rollers had to stay closer to the paver compared to normal conditions. One contractor added a wax in their PA mixture to improve workability and compactibility. For the early skid resistance both sections were gritted with fine aggregate.

Photo 6: Overview of the laying process.

Photo 7: Gritting from the roller.

Because only the left lane had to be paved the adjacent PA in the right lane is very sensitive for damage particularly at low temperatures. It is known that if one lane is maintained it will easily result in premature ravelling of the adjacent lane. This is caused by one or a combination of the following items:

- fast milling process, which can initiate cracks in the old PA layer
- driving of rollers over the old brittle PA, which causes microcracks in the bonding bridges between the aggregates of the old PA
- spilling of loose fresh PA material on the old PA which can fill the air voids in the old PA, this can later result in cracks due to traffic loading

All equipment was transported to the test section on a trailer to avoid damage by the equipment itself to the existing pavement. One contractor used the Surface Jet in front of the milling process to control a sharp edge instead of an uncontrolled brittle milling process. Compacting the edge of the section with new PA+ can result in damaging the old adjacent PA. Special attention was paid to avoid this damage. After compacting the new PA+ a rejuvenating bitumen emulsion was sprayed into the adjacent existing PA to cover the aggregates with new binder and fill microcracks which may have been the result of the compaction process. One contractor preheated the adjacent existing PA to prevent the emulsion to get immediately frozen in contact with the cold existing PA.

Normally paving at sub-zero conditions is not allowed according to employment regulations. But in this particular case it was allowed because of the research goals. Workers were protected with sufficient clothing and warm drinks and meals. All equipment was protected against freezing with anti-freezing liquids.

From the construction of the two test sections it can be concluded that it is possible to pave under sub-zero conditions without loss of quality if:
- the paving process is analysed thoroughly and critical parameters are addressed individually
- adequate measures are taken and planned accurate
- execution of the work is according to this plan

But it must be stated that even with these remarks the management of risks is not equal to full risk control. The lack of experience and the possibility of changing weather conditions can easily result in a lesser quality. Therefore boundaries must describe to what extent paving can be performed.

5. RESULTS

5.1 Monitoring process

This section describes the outcomes of the monitoring process. The aim is to discuss (the effectiveness) of the monitoring procedure rather than presentation of the actual measured data (although some of the measured data are brought in to illustrate). This section is divided in four sub sections. First will be the description of the conditions, specifically the weather conditions. Second will be the initial PA temperature data. Followed by the cooling process registration. And finally the monitoring of the machine movements.

<u>Conditions:</u>
The contract stipulated that work be carried out within a very strict (narrow) temperature window, the limits of which were set out in the contract documentation. Essentially, a “Frost-Go” signal would be given 48 hours before work was to commence if:
- The chill factor during working hours was not below -6°C;
- Daytime temperature was +5°C and the maximum temperature during construction was +2°C;
- The temperature of the existing asphalt was a maximum of +5°C during working hours;
- Wind speed was a maximum of 5m/s;
- There was no rain or mist;
- A sustained “cold” period was needed for work to proceed, defined as a minimum of three consecutive days with a minimum temperature of 0°C or below. The test section would be constructed, at the earliest, on the third day of such a “cold” period.

During construction, weather conditions were monitored using a portable weather station mounted in the A58 freeway median. The actual weather conditions experienced whilst construction was carried out between 01:45 and 05:00 fell within the narrow limits set by RWS with an average temperature of -0,1°C, an average wind speed of 0,5m/s and wind chill average of -2,3°C.

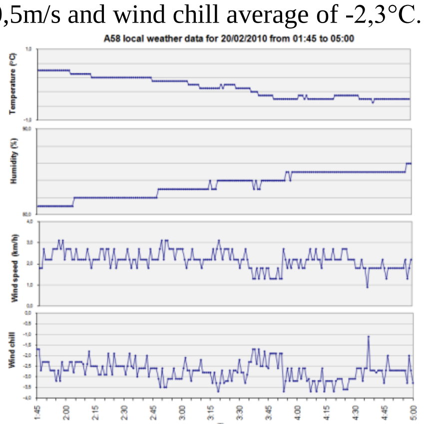

Figure 1: Weather data.

Initial PA temperatures (measured behind the screed):
The set up with Infra red line scanner in combination with GPS receiver proved to work well on one section and did not work on the other. The figure below shows a segment of the Temperature Contour Plot (TCP) (i.e. the initial temperatures beyond the screed plotted against time) of the section with the IR-line scanner working well. This type of measurement provided rich detail information.

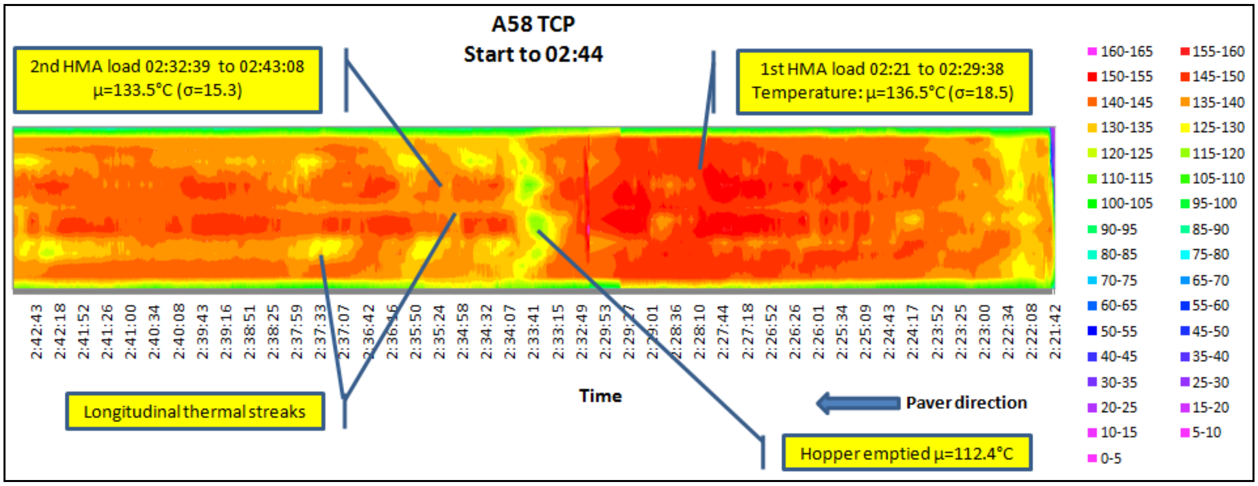

Figure 2: PA temperature contour plot.

The TCP shows for example longitudinal thermal streaks occurring during paving operations. These thermal streaks are visible in two forms. In the first, a longitudinal streak is visible near the centre of the paver with the temperature in the streak dropping by as much as 15°C when compared to the surrounding PA. In the second, longitudinal segregation is evident in thermal streaks running parallel to the centre-line in the area of the conveyor belts that transport asphalt through to the paver's augers. These temperatures differentials are greater than those in the centre with the surface temperature dropping appreciably in some places along the test section. The thermal streak phenomenon has previously been observed by this research team on other PQi's. In [5] was found that thermal streaks represents an area of weakness that has low resistance to thermal contractions. This type of failure results in the development of longitudinal cracks, appearing in the first few winters following construction work.

The IR-linescanner data was also used to compare joint warming mechanisms employed by Contractor 1 to improve the joint of the existing (cold layer) and newly laid PA surfacing. The joint warming resulted in the heated longitudinal joint area having a surface temperature 20°C higher (on average) than the non-heated open side.

Unfortunately, is was not possible to gain the same range of insights for Contractor 2 whose paver was fitted with the rental IR-linescanner. With no prior testing of the IR-linescanner, the combination of a rental IR-linescanner and a "foreign" laptop not normally used on PQi's, resulted in problems for the Direct Data Exchange facility that allows automatic data transfer and thus, no consistent IR-linescanner data or data stream files could be recorded. Fortunately, a backup methodology used on earlier PQi's during the formative stages of this research [6] was put in place just in case using a (rental) IR-linescanner proved problematic. Images taken with a hand-held infrared camera, every five metres behind the paver screed, provided sufficient data to determine the extent of temperature homogeneity of the test section (see Figure) and to visualise the truck changes. The incident log compiled during construction operations revealed the same operational behaviour found with Contractor 1, that the paver stopped every time a new load of asphalt arrived with the result that the surface temperature dropped depending on the length of the stop. The incident log and paver GPS data showed that no prolonged stops occurred (μ = 1.8 minutes) and hence the stops had little effect on the overall cooling of the mix. In addition, the contractor limited the mixing of colder PA that normally falls from the sides of the hopper and remixed with the warmer mix, by keeping the hopper flaps open. An additional strategy employed by the contractor was to remove the first 2 to 3 tons of PA from the truck and dispose of it, before unloading the rest of the mix into the hopper. Joint warming was also employed for this test section. However, the resolution of the hand-held infrared camera is rather limited when compared to the IR-linescanner and hence does not show the same level of detail. Hence, no inferences could be made regarding the joint warming or the presence of the thermal streak phenomenon found with Contractor 1.

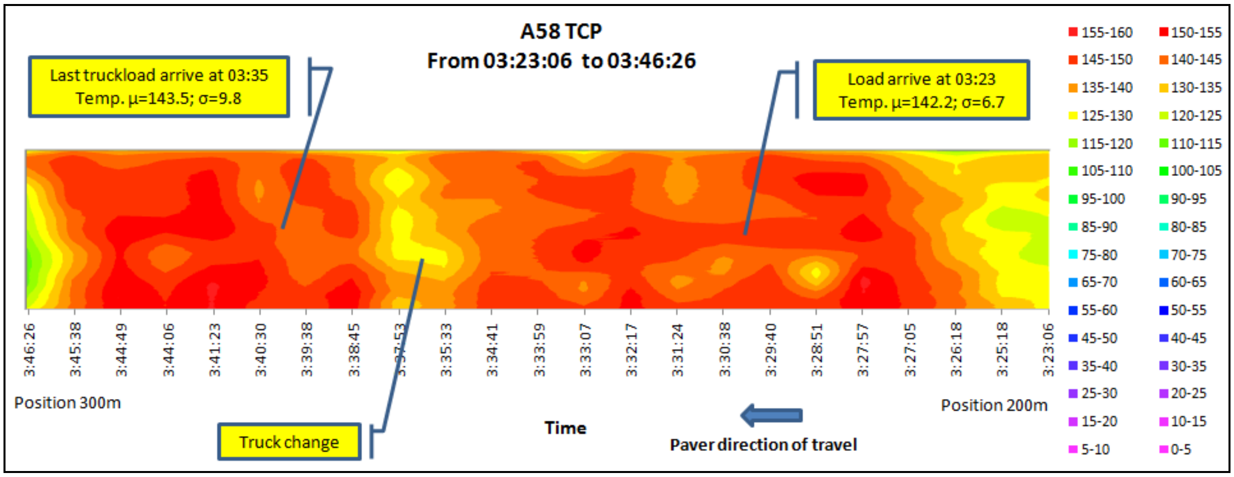

Figure 3: Typical Temperature Contour Plot for Contractor 2 - last 100m.

Overall the measuring of initial temperature with the IR-Linescanner provided useful to monitor and observe:
. initial PA temperature (homogeneity);
. differences between truck loads (logistics);
. cooling effects during stop-go situations;
. effect of the joint heater;
. cold spots and temperature segregation (potential weak spots regarding quality)
. effects of the pavers geometry, its internal PA transport, effects of paver operation (opening/closing hopper)

Registration of the Cooling process:

PA cooling rates were determined at the two positions stipulated by RWS at positions 100m and 200m from the start of the test section. Surface and in-asphalt temperature measurements were recorded from the moment the paver passed those positions. Some data loss occurred with the in-asphalt temperature measurements due to a technical error, with the result that no comparisons could be made between the surface and the in-asphalt cooling rates. Nevertheless, the surface cooling rates were compared with the theoretical cooling rates derived from the PaveCool Freeze software developed by Timm et.al (2005). The surface cooling correlates well with the theoretical rates derived from PaveCool Freeze with R^2 values above 0.9 (see). It appears that the tool shows the layer to be cooling off at a faster rate than has actually occurred given the weather conditions. Under the given sub zero temperatures, the ZOAB layer tends to cool some 30°C over the first 15 minutes and approximately 15°C over the next 15 minutes before slowly levelling off.

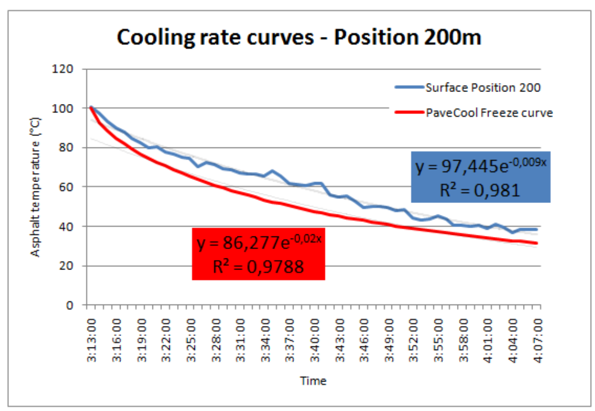

Figure 4: Surface cooling.

Monitoring machine movements

As mentioned earlier, additional GPS equipment had to be rented for following one of the PA construction teams. Contractor 1 hired an entire survey team to conduct its GPS measurements using a hired high-end Topcon system and Contractor 2's equipment was fitted with ASPARi's Trimble system.

The paver speeds were derived from the registered GPS data. Both paver operators maintained constant speeds during paving of 5m/min and 5.8m/min for their respective test sections. In both cases, the only exception is that the pavers stopped for an average of ±2 minutes for each new load of ZOAB. These stops were verified using the incident log compiled by the research team during paving operations.

The rollers and their movements were all registered except one for contractor 1. To avoid roller damage a small tandem roller was used to compact the joint without being fitted with a GPS receiver. That small roller could therefore not be tracked during its operations. This small roller was not part of the original operational plan devised by the contractor prior to construction operations being carried out. The decision to use the small roller was taken shortly after construction commenced. The initial strategy to use a special single drum mounted on the 10 ton tandem for the joint, was abandoned in order to limit the damage to the adjoining existing surfacing layer. The construction team was not happy with the result and therefore mobilised the small tandem (without mounting a GPS receiver first). The Compaction Contour Plots (CCP) for the two heavier tandem rollers is given in figure 5. Furthermore, 20 minutes of GPS data loss occurred between 02:43 and 03:03 resulting in an incomplete view of the Bomag tandem roller's compaction operations. It is clear from the CCP, that from position 180m onwards, the operator has tended to concentrate on the middle of the paved lane where the average number of passes are almost double that of the sides.

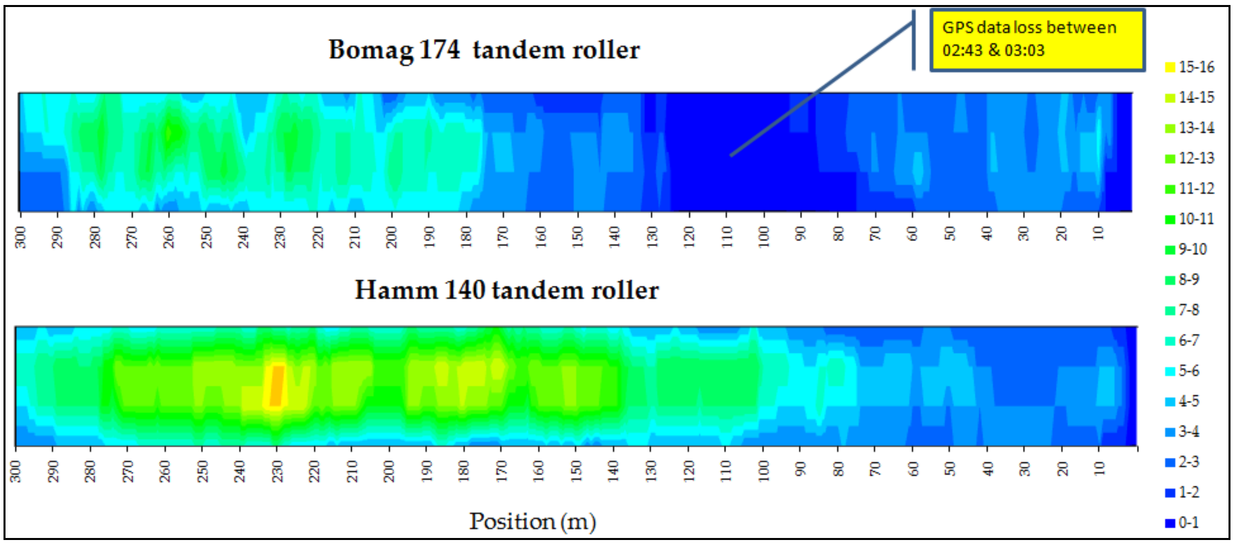

Figure 5: Compaction Contour Plots for Contractor 1.

The lack of compaction passes on the longitudinal joint side has been compensated by using the 2.5 ton small tandem roller for joint compaction. It is difficult to determine whether this additional joint compaction was adequate given the absence of GPS data. A similar pattern to that observed for breakdown rolling emerges for the Hamm 14 ton tandem roller used for finishing operations (see bottom of figure 6. Also, two zones of compaction are clearly visible over the length of the test section. The first 100m has received significantly less compaction passes compared to the rest of the test section.

For Contractor 2, the compaction operational strategy appears to be quite different (see Figure). The contractor uses similar weighted rollers (to that of the other contractor) with breakdown rolling undertaken using a Bomag 10 ton tandem roller and final rolling using a Hamm 14 ton three-drum deadweight roller. The tandem roller operator covers the entire test section tending to concentrate on the middle of the lane. Two zones of compaction are visible with the start of the test section receiving less passes than the end and the number of compaction passes steadily increases from the start to the end. Whilst the operating strategy of the tandem roller operator appears to be clear, the role of the three-drum roller is unclear. The operator starts off compacting the whole width of the lane, then after approximately 90m tends to only compact the longitudinal join area. The overall result is that there is significant variability in the number of compaction passes applied to the test section with the area next to the longitudinal join having received the most compaction passes.

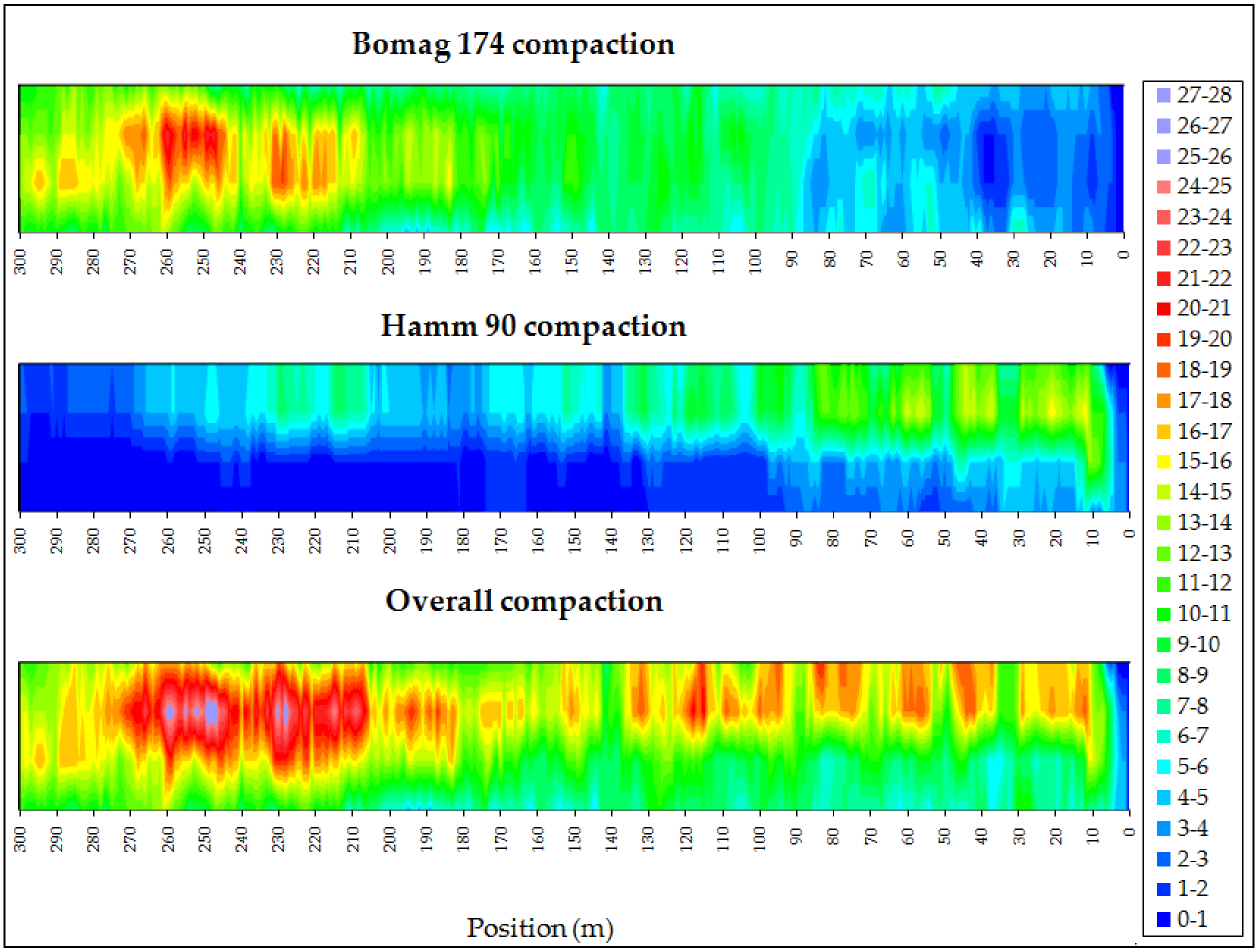

Figure 6: Compaction Contour Plots for Contractor 2

Overall the registration of the machines' movements provided useful to monitor and observe:

- speed of the paver, changes in speed of the paver and stop-go situations (time-place-duration), behaviour of the roller compared to the devised operational plan (consistency);
- operational behaviour of each roller, the coverage per roller, the coverage of the rollers combined;
- variation in the coverage between locations;
- variation in operators' choices in relation to time/distance to paver, and regarding the temperatures of first – last roller pass per location.

5.2 Laboratory results and interpretation

In table 1 the average results are given of the tests carried out on drilled cores.

Table 1: Average results of RSAT, Cantabro and ITSR tests.

Avarage results of RSAT, Cantabro and ITSR tests on cores of the test site					
	RSAT (loss of stones in g)	Cantabro (loss of stones in g)	Indirect tensile strength (MPa)	Indirect tensile strength after conditioning in water (MPa)	ITSR (%)
Contractor 1	17.0	47.4	1.15	0.99	86.2
Contractor 2	9.3	37.6	0.91	0.74	81,4

From comparison with other similar RSAT research [7] (also per specimen cores with a diameter of 150 mm were tested) of five PA+ mixtures laid under normal weather conditions, it can be concluded that the resistance to raveling of both PA+ test sections is excellent. The average loss of stones determined in [7] was 51.2 g. One outlier was skipped, because this PA+ mixture contained an experimental filler.

Normally the Cantabro test is carried out on Marshall specimens and there is hardly no experience with Cantabro tests on drilled cores. The requirement for loss of stones of Marshall compacted specimens is ≤ 30%. Assumed is that the loss of stones of cores is much more due to the weaker outside of the cores. Stones can easily break out in comparison with Marshall specimens. So unfortunately the Cantabro results can't be interpreted properly.
In the Dutch national standard [1] the requirement for water sensitivity is $ITSR_{80}$, so both PA+ mixtures fulfil this requirement.
If the Cantabro results are excluded, it can be concluded that the resistance to raveling and the water sensitivity are sufficientand can be compared with results of PA laid under sub-zero conditions behave similar like PA+ laid under normal weather conditions.

5.3 Laser mesurements

ARAN laser measurements are carried out after laying (1 March 2010), after 6 weeks (13 April 2010) and after 28 weeks (22 September 2010) to investigate if raveling developed in time. The results of the laser measurements are summarised in table 2 . Before, in between en after the test site also old consisting PA was measured. Light ravelling means that 6 to 10% of the original amount of stones is driven out, moderate ravelling means that 11 to 20% of the original amount of stones is driven out and serious raveling means that more than 20% of the original amount of stones is driven out. Supplementary is from the Stoneway data the average percentage loss of stones calculated per 10 meter for the left and right wheel track (see figure 7).

Table 2: ARAN laser results – total percentage stone loss.

test	hm	1-3-2010	13-4-2010	22-9-2010	13-9-2011
site	61,0	4,1%	3,8%	4,1%	6,2%
	61,1	4,7%	4,5%	4,7%	6,0%
B	61,2	2,6%	1,8%	1,7%	2,6%
B	61,3	2,8%	2,5%	1,5%	2,0%
B	61,4	2,5%	2,3%	1,4%	2,2%
	61,5	6,3%	5,9%	6,4%	8,7%
	61,6	6,8%	6,8%	7,2%	10,8%
	61,7	6,6%	7,2%	8,0%	12,1%
A	61,8	2,3%	1,5%	1,0%	1,4%
A	61,9	2,7%	2,1%	0,8%	1,6%
A	62,0	3,0%	1,8%	0,7%	0,9%
	62,1	5,8%	5,9%		
	62,2				

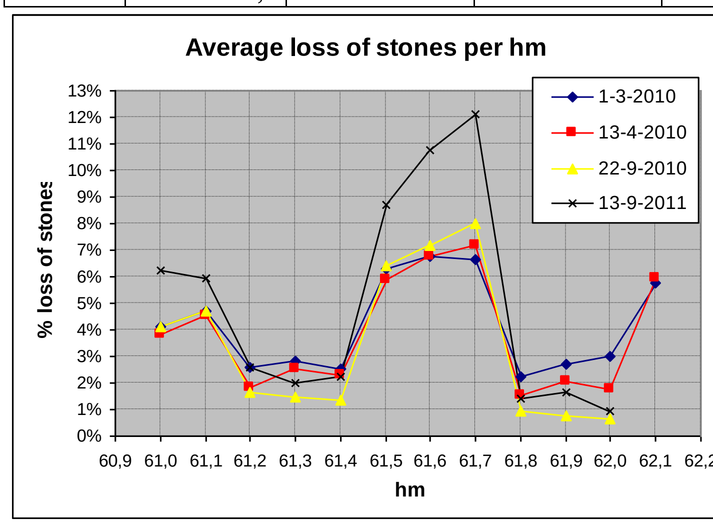

Figure 7: Results ARAN laser measurements.

From the ARAN laser results it can be seen that the light raveling on the test sites is considerably lower than in the old existing PA road sections. The percentage moderate and serious raveling is for both test sites close to zero.
The general careful conclusion is that more than half a year after laying no sign is to be seen of premature raveling in the test sites laid under sub-zero conditions. To build these conclusions stronger it is recommended to follow the degree of raveling with laser measurements of these test sites in time.

6. CONCLUSIONS

The test sections on motorway A58 demonstrate that paving Porous Asphalt under sub-zero conditions is possible. After analyzing the paving process the critical parameters were addressed and consequently measures were taken by the two contractors. Both test sections have been constructed successfully. From the laboratory and ARAN results it can be concluded that the quality is at least equal compared to paving Porous Asphalt under normal conditions.

Registration of the equipment movements with GPS and registration of the temperature and compaction of the asphalt in time are very useful instruments to monitor the laying process.

7. DISCUSSION

The measures that had to be taken to lay PA+ under sub-zero conditions cost a lot of extra budget, logistic arrangements and have a negative influence on the environment because of the extra energy consumption and noise production (SurfaceJet). Taking into account of that, Rijkswaterstaat intend only to lay PA under sub-zero conditions in emergency cases and not as a normal maintenance method in winter time. So, if one lane of an important motorway suddenly has to be closed due to severe raveling caused by frost damage or other and the frost period will stand for a longer time, Rijkswaterstaat will give order to lay PA under sub-zero conditions to prevent extra traffic hindrance. Also when the traffic safety is in danger Rijkswaterstaat will give order to maintain the motorway under sub-zero circumstances.

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