FOAMING OF BITUMEN – A KEY PROCESS FOR DIFFERENT LOW TEMPERATURE ASPHALTS

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ABSTRACT

To reduce the energy consumption and CO2 emissions during asphalt production, several technologies have been developed during the last years. One of these technologies is the reduction of the asphalt mixing temperature by using foamed bitumen. Foaming the bitumen reduces the binder viscosity temporarily and increases the volume as well. Homogenous foams are produced by injection and mixing of water into hot bitumen. Therefore the key component for the foaming process on the asphalt mixing plant is the foam generator. At present two principles are widely used: mixing chambers and plug flow reactors.

The feasibility of producing warm mix asphalt on a conventional batch plant equipped with a plug flow foam generator was proofed in a field trial. The temperature reduced W-ecophalt® asphalt mixture was produced at 115°C with a process based on a two phase system resulting in a complete coverage of the aggregates. Asphalt production and laying was attended and analysed. Mechanical properties equivalent to conventional hot mix asphalt were found.

Keywords: Energy savings, environment, warm asphalt mixture, foam bitumen, field trial

FOAM BITUMEN –PROMISING WARM MIX TECHNOLOGY

Asphalt consists of roughly 95% of aggregates and about 5% of bitumen that binds the aggregates. The aggregate is coated by the bitumen during the mixing process at elevated temperatures, because regular bitumen shows a high viscosity at ambient temperatures. In order to generate a homogenous thin bitumen film at short mixing times, a viscosity as low as of 0.2 Pa s is recommended [8]. Therefore, traditionally the bitumen needed to be heated. To maintain the elevated temperature of the bitumen during mixing and paving, the aggregates are heated to high temperatures. Therefore, asphalts are traditionally mixed at temperatures around 160 - 180 °C. The aggregates are heated up on asphalt mixing plants with an output of several hundred tonnes of asphalt per hour. The high temperatures define the energy consumption and in parallel the CO_2 emissions per ton of asphalt (see figure 1). As a rule of thumb, by lowering the asphalt temperature from 180 °C to 115 °C, the energy consumption on average is reduced by 1.5 kg oil per ton produced asphalt.

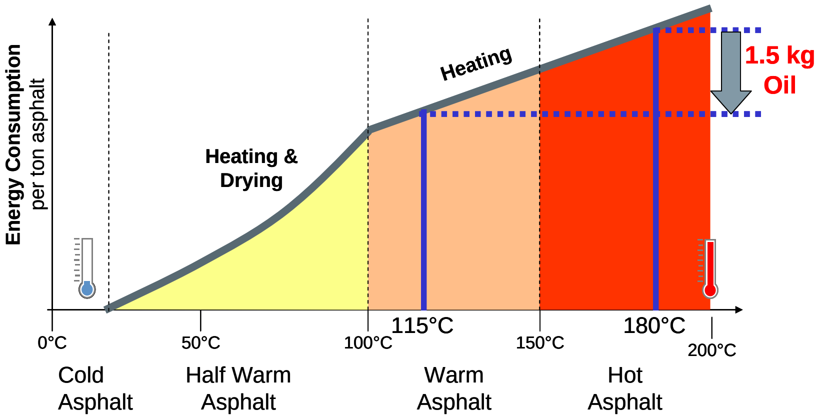

Figure 1: Energy consumption per ton of asphalt as a function of the asphalt temperature

In the last years, an array of technologies allowing a significant reduction of the production temperature has emerged. Popular technologies for temperature reduction are based on a combination of addition of waxes and other agents, changing the mixing sequence and the use of foamed bitumen. Foaming the bitumen increases the volume of the binder and as a consequence, reduces its viscosity temporarily. After the foam has collapes, the bitumen shows the same properties as before [7]. This paper focuses on the approach using foamed bitumen and its production. For foaming-based low temperature asphalt (LTA) technologies, the foam generator is the key component on the asphalt mixing plant.

Bitumen foam – The underlying principles

Foams are produced by incorporating gas into the liquid and creating bubbles. The total volume of the foam is proportional to the amount of gas incorporated and the size of the gas bubbles determines the stability of the foam. Liquid foams are thermodynamically unstable systems due to their high gas-liquid interfacial area. The main mechanisms to destabilize foams decrease of the system's overall free energy: drainage (creaming), coalescence (film rupture) and Ostwald ripening (disproportionation). When combined, these mechanisms increase the gas bubble size and may collapse the foam within seconds after the gas incorporation. Therefore, the size of the gas bubbles determines the stability of the foam. [3].

Foaming of bitumen dates back to the 1950s, when steam was injected into hot bitumen. To reduce the equipment's complexity and the difficulties with controlling the added amount of steam, a modified process was developed by introducing cold water under pressure instead of steam [8]. Nowadays, foamed bitumen is produced by the injection and mixing of water into hot bitumen. The water is dispersed mechanically into small droplets whereas heat from the hot bitumen energizes the water droplets beyond the latent heat of steam defined by the pressure in the foam generator or expansion chamber. Therefore, the water evaporates and expands. A mixture of small steam bubbles and bitumen is formed. This foam is released directly into the asphalt mixer. Due to the low viscosity of the bitumen foam, the aggregates need to be warmed up to lower temperatures saving significant amounts of energy and cost.

The way to warm mix asphalt

Initially, the bitumen foam technique was used with cold aggregate to stabilize soils and then was improved to stabilize base courses of roads. The experience in various countries has shown that cold foam asphalt produced at ambient temperature does not reach the properties of hot mix asphalt required for heavy duty roads. Higher void content of the pavements and incomplete coating of larger aggregates are believed to be the main reasons for this lower performance.

The larger the particles, the less surface of the aggregates are coated at lower temperatures. Jenkins [5] showed in his research using a continuously graded Hornfels that lower mixing temperatures for asphalt using foam bitumen leads to incomplete coating of aggregates (figure 2). This research was on asphalt temperatures up to 85 °C.
Recent research focuses on the use of foam bitumen at mixing temperatures around 100 °C. Amongst others, Larsen [6] and Opel [7] showed that at warm temperatures slightly above 100 °C asphalt produced with foam bitumen shows better quality. In addition, van de Ven [9] reports similar results at half-warm temperatures around 100 °C. However, these results are mainly based on tests carried out in the laboratory. Some field tests and trial sections are realized but only limited long term studies are available. Currently various research projects in different countries are under way.

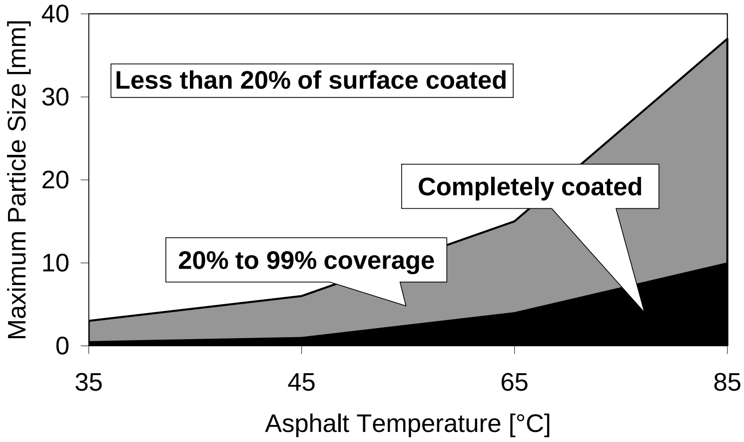

Figure 2: Effect of asphalt temperature and particle size on aggregate coating [5]

THE PLUG FLOW FOAM GENERATOR

Our field experience on asphalt plants and trials shows that the foam quality depends highly on the used bitumen and the process parameters (e.g. pressure, flow rate, temperature, etc.). To allow warm mix asphalt with foam bitumen to reach quality levels of conventional hot mix asphalt, foam generators must provide the possibility to be adjusted to the different operating conditions. On the contrary, most foam generators available on the market arose from the continuous production of cold recycling asphalt and have been optimized in recent years according to field experience in this field of application. Given the quality requirements for cold mix asphalt due to the fact that the traditional application of the foam generators is in the continuous asphalt production, these foaming units are straight forward installations with simple on/off principle. They are typically based on fixed foam production parameters and lack possibilities for variation.
There is a variety of different foam generator described in literature and partly also in use. The prevailing principles are plug flow reactor and mixing chamber. Other types of foam generator do exist, but are only applied in niches. In the following section, we will focus on the working principle of the plug flow reactor and illustrate its application.

Plug flow reactor

The plug flow reactor group is characterized by their robust and cost-effective design. They mainly consist of a bitumen pipe with water injection. As figure 3 shows, the water is injected through a nozzle directly into the hot bitumen flow in the pipe. The two components mix before being released into the mixer. Depending on the system, static mixers and/or expansion chamber are integrated inline, to homogenize the distribution of water/steam and bitumen. Advantages of this design are the straightforward construction principle and easy cleaning. This results in a robust overall process.

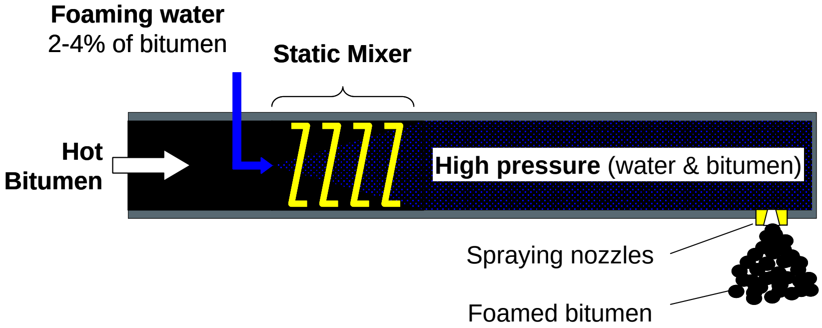

Figure 3: Plug flow reactor principle

The critical process to produce homogenous and stable foam is the dispersion of the water in the continuous bitumen phase. Therefore the key components for the plug flow foam generator are the injector of the water into the bitumen flow, the type of flow in the foam generator and the pressure of the water-bitumen-mix. As shown later in chapter 3, elongational flow is needed for an effective drop break up and dispersion of the water in the continuous bitumen phase. In addition, the pressure in the foaming unit should be adapted to the bitumen temperature in order to keep the water in the liquid phase as long as possible. As the pressure of the water vapour rises with an increase in temperature, the pressure in the foaming unit is adjusted to keep the water in its liquid state. Figure 4 shows the general interdependency of vapour pressure and the temperature of the water.

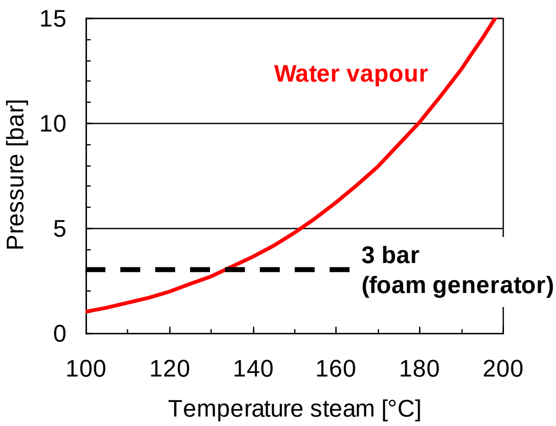

Figure 4: Water vapour pressure as a function of temperature [2]

DROPLET DEFORMATION AND BREAK UP

Droplet size defines the quality of the foam

The stability of the foam bubbles and the volume of the foam are widely seen as the key quality criteria to assess the bitumen foam. As mentioned above, the dominant physical process that influences the stability of the foam is the gas bubble size. Small bubbles with a narrow size distribution are more stable. Additionally bitumen is a visco-elastic non-newtonian fluid. Viscoelasticity leads to an increase of interfacial tension and to a stabilization of the droplets.

To create small, uniformly distributed bubbles, a three step process ideally takes place (see figure 5). First the water is evenly distributed in the hot bitumen, second the droplet break-up as much and as fast as possible and third the evaporation. The distribution of the water droplets is done by dedicated water nozzles. In order to foster a fast break-up of the water droplets, the basic influences of the foam generator's geometry and the fluid dynamics on the drop formation need to be understood. Important factors for droplet break-up are the viscosity ratio between the water/vapour and the bitumen, the type of flow, the residence time and the history of experienced velocity gradients in the foam generator.

When a droplet breaks into smaller volumes, its specific surface and thus the interfacial area are increased. It is important to keep the droplets or bubbles isolated to avoid coalescence of small spheres into larger ones. In reality effects like interaction of droplets or an increase of the shear rate rise the probability of collisions and coalescence to larges bubbles.

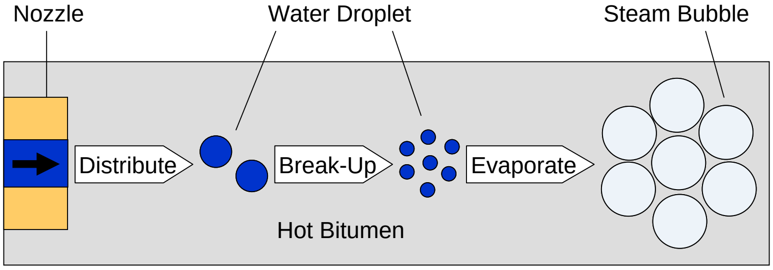

Figure 5: Creating of bitumen foam

Mechanism for droplet break-up

Breaking-up of water droplets in the hot bitumen environment is a key process for foaming. As known from research in different domains, droplet deformation and the eventual break up depend on the interfacial tension stresses as well as the viscous and pressure stresses that are applied by the surrounding the continuous phase. When flow induced stresses exceed the interfacial tension stresses, the droplet is stretched which may result in rupture [1]. This ratio is described by the dimensionless Weber number We

$$We = \frac{\tau \cdot l}{4 \cdot \sigma}$$

symbol	general	bitumen foam generator
t	flow induced stress	stress the continuous bitumen phase upon the droplet
l	characteristic length	radius of the water droplet
σ	surface tension	surface tension of the water-bitumen-interface

The critical Weber number We_{crit} characterizes the flow regime where droplet deformation changes into droplet break-up [4]. For $We > We_{crit}$ break-up (structure change) occurs, for $We < We_{crit}$ deformation takes place. We_{crit} depends on the type of flow and the viscosity ratio of the continuous (here: bitumen) and dispersed phase (here: water/vapor). In the foam generator, the viscosity rate between bitumen and water is slightly below 1, as long as the water has not evaporated. In figure 6 the critical Weber number We_{crit} is shown as a function of the viscosity ratio and the flow type. The target area for an efficient drop break up is indicated by a red rectangle: Viscosity ratio < 1 and $We > We_{crit}$. From figure 6 can be concluded that for an effective drop break up the viscosity ratio should be close to 1 and the interfacial tension low, hence the disperse phase should be liquid not gaseous. In addition shear flow is less effective than elongational flow, because the critical Weber number is lower at comparable conditions.

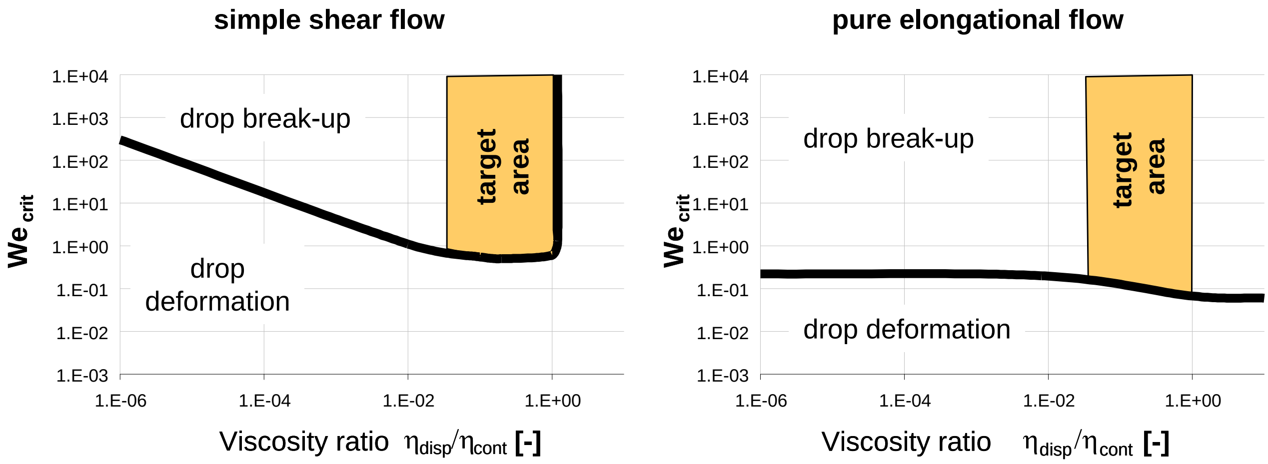

Figure 6: We_{crit} for shear flow and for pure extensional flow, adapted from [4]

FIELD EXPERIENCE WITH WARM ASPHALT USING A PLUG FLOW FOAM REACTOR

To proof the feasibility of the plug flow reactor process several field trials with warm asphalt have been conducted in the past years. In the following section we describe an asphalt paving site using warm asphalt with foam bitumen. We report the results of the large scale field production and lay down of warm mix asphalt. The asphalt mix was produced with a two phase mixing process and laid on a principal road close to Berne (Switzerland) in June 2010.

Production on an conventional hot mix asphalt plant

A conventional batch plant equipped with a foaming installation was used for the material production. Figure 7 shows the principle of this type of asphalt mixing plant: the minerals are added via cold feeders on a conveyor belt and fed into the rotary drum dryer where the aggregates are heated and dried. From the rotary dryer, the hot aggregates are conveyed via a vertical elevator to the screen that separates the mineral in different grain size fractions. These fractions are stored in hot silos, dosed using scales and mixed in a twin-shaft paddle mixer with hot bitumen and potentially additives. Reclaimed asphalt is directly added into the mixer. This addition can be cold or heated by a parallel drum. In Europe, most of the asphalt plants are of the batch type.

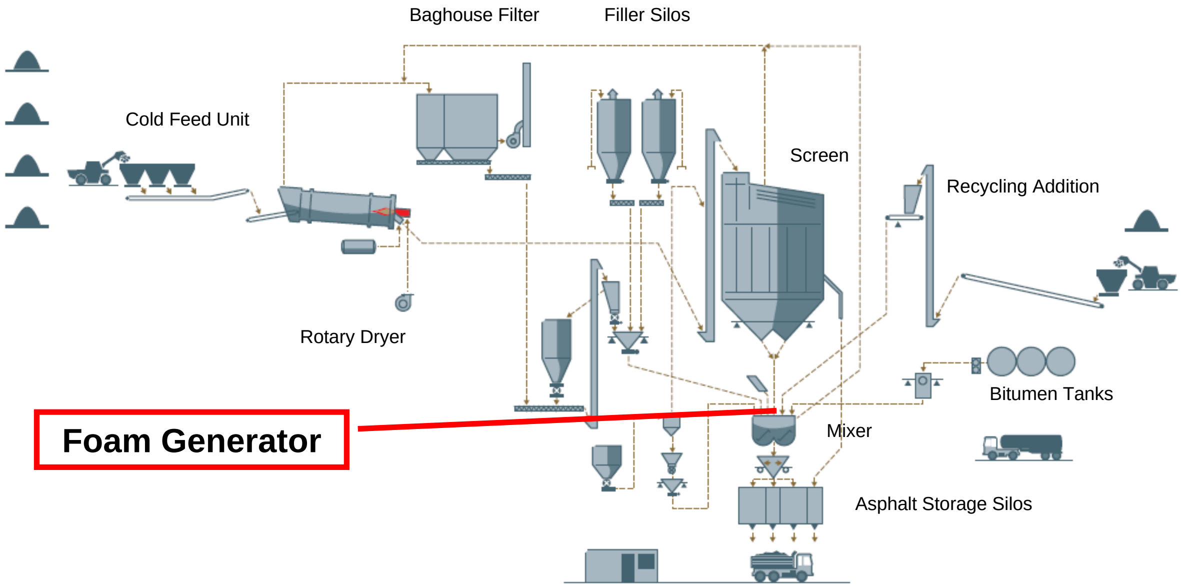

Figure 7: Batch type asphalt mixing plant

In figure 8 a picture and the outline of the foaming unit as installed on several asphalt mixing plants can be seen. To assure a homogeneous mixture, the plug flow reactor is connected to a foaming bar which releases the foam uniformly through five spray nozzles onto the aggregate in the twin-shaft mixer. Using a twin-shaft paddle mixer increases the flexibility of the mixing process and ensures an adequate coating of the aggregates with bitumen due to the high shear field in the mixer.

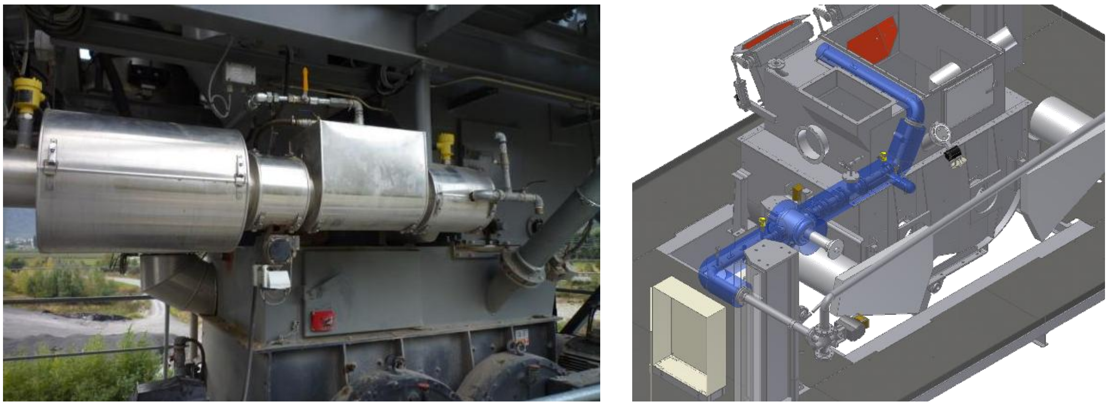

Figure 8: Picture of foaming unit on asphalt mixing plant and schematic illustration

One of the established warm mix processes using foam bitumen is the WAM foam® process [6]. For this approach the lower production and laying temperatures are achieved by a two component binder system that introduces a soft binder and hard, foamed bitumen grades. The asphalt mixing takes place in a defined order: First the soft bitumen is transferred to the mixer and mixed with the aggregate to pre-coat the aggregate. Secondly the hard bitumen is foamed and mixed with the pre-coated aggregates. This process is used in northern Europe. Besides this process principle other approaches do exist, e.g. foaming all the bitumen or using other mixing sequences. Several asphalt producers are introducing their variations of foam bitumen processes. A flexible asphalt mixing plant equipped with a plug flow foam generator is key to produce all kinds of warm mix asphalts.

For this field application a variation of this process was applied. The W-ecophalt® base-wear-course was designed as a AC T 22 N TDS and has been produced with a warm addition of 50 % reclaimed asphalt. The W-ecophalt® asphalt mix production used a 250/330 bitumen as a soft component for pre-coating. The hard, foamed binder component was a 35/50 bitumen at 170°C. Both types of bitumen did not contain any additives nor was any additive added. The asphalt material was laid on an overland main road with a layer thickness of 8 cm.

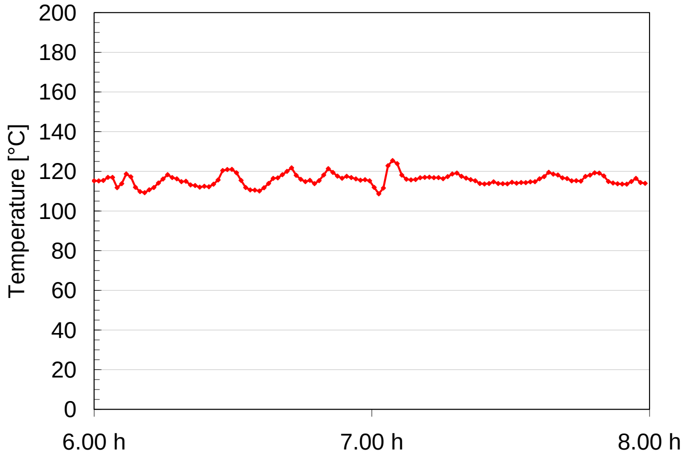

Figure 9: Warm asphalt mix temperature (morning hours as example)

Temperature of the mixed asphalt was between 105 and 115°C during the whole production. Figure 9 shows the evolution of the warm asphalt mix temperature between 06:00 and 08:00, as measured on the plant. The fluctuation showed to be only +/- 5°C. A constant foam generator pressure is important for stable conditions in the foaming bar. Especially in the batch mixing asphalt plants maintaining a constant foam pressure is crucial due to the starting and stopping of the foaming for each batch. As can be seen in figure 10 the measured pressure of the bitumen-water-mixture in the foam generator is 3 bar +/- 0.1 bar, which is rated very constant. The water injection pressure needs to be higher than the foam bar pressure, to ensure the distribution of the water droplets in the hot bitumen. The field measurements revealed that the pressure in the water injection pipe was 5 bar +/- 0.5 bar.
At a pressure of 3 bar the maximum temperature to prevent the water from evaporating is 130°C as can be seen in figure 4 (dashed line indicates 3 bar). The calculated temperature of the water-bitumen-mixture is 160°C if the water remains liquid or 130 – 140 °C if all water evaporates. Since the calculated temperature of the water-bitumen-mixture is above 130 °C, the water evaporates and an equilibrium of the water-steam-system is found.

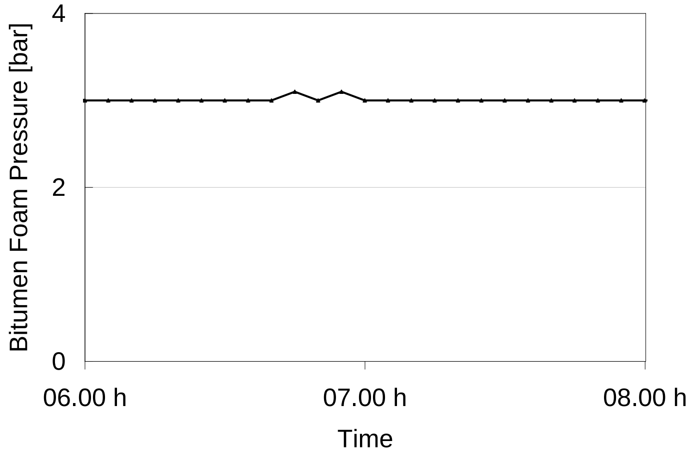

Figure 10: Maximum foam pressure during batch production (morning hours as example)

Construction site

On the day previous to the laying the underground was prepared by milling both lanes (see figure 11) and spraying bitumen emulsion. The quality of the bituminous underground was not fully uniform due to a varying layer thickness of the old wear and base course. Nevertheless 3 – 5 cm of the previous pavement remained and only in some places the bituminous layer was completely removed and compacted earthworks became visible. Pictures of the construction site can be seen in figure 12.

Figure 11: Underground after milling and before laying of the asphalt

Figure 12: Two pavers and roller compactors, e.g. AV 95-2 ACE (with GPS based compaction control ACEplus).

The road workers and truck driver stated that the warm mix asphalt is to compact like conventional hot mix material and even sticks less to the truck or surfaces. After finishing the construction site, no ruts were observed.

During the lay down of the warm asphalt the material density was determined by Troxler probe measurements. In Fig. 15 the evolution of the compaction can be seen as a function of time and roller passes. The paver reached a pre-compaction of up to 1900 kg/m3 or 80 % of laboratory Marshall density. After the roller compaction a minimum density of 97 % of the Marshall density was achieved for all measured spots, which corresponds to the usual values measured at hot mix construction sites. As can be see below in Section 4.3., the drilling cores showed results similar to the Troxler probe measurements.

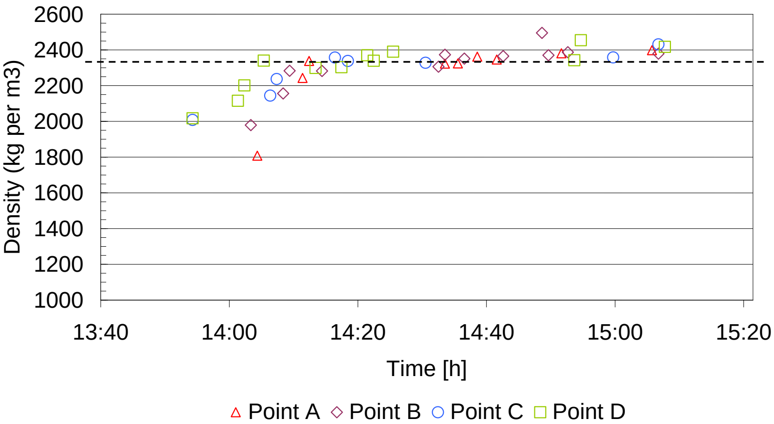

Figure 13: Density of pavement (Troxler) for 4 different points as a function of time and roller passes. Dashed line = 97 % of the Marshall

Mechanical analysis

To ensure quality, the warm asphalt has been characterized according to the European hot mix standard EN 13108-1: 2006 / AC: 2008. The bitumen content in the asphalt mix was 5.05% thus slightly higher than the calculated 4.9 %. As the bitumen content is within the tolerances no impact on the mechanical properties was found. The end penetration of the recovered bitumen was 49 1/10 mm. The characteristics of the Marshall specimen are shown in figure 14. The

Marshall stability, Marshall flow, indirect tensile strength and water susceptibility of the temperature reduced W-ecophalt® warm mix asphalt meet the requirements of conventional hot mix asphalt. The water susceptibility of the Marshall specimen shows a value of 92% and meets the requirements for hot mix asphalt (>70%; ITS Dry 1.104 MPa, ITS Wet 1.015 MPa).

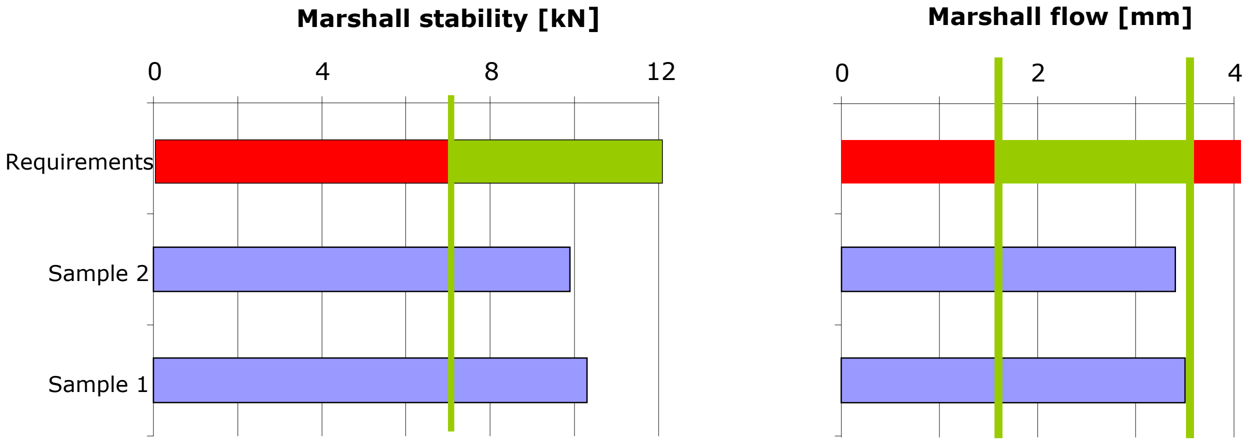

Figure 14: Marshall specimen from plant material: Requirements fulfilled

The Marshall specimen showed an air void content of 2 Vol.-%. In comparison for the drilling cores a void content of 2.41 – 3.41 % (average 2.98%) was measured as shown in figure 15. A reason for the low void content is the slightly increased bitumen content. The values for the air void content are all within the tolerance. The degree of compaction was within specifications for every drilling core and also for the average value (average 99.1%, required > 98%).

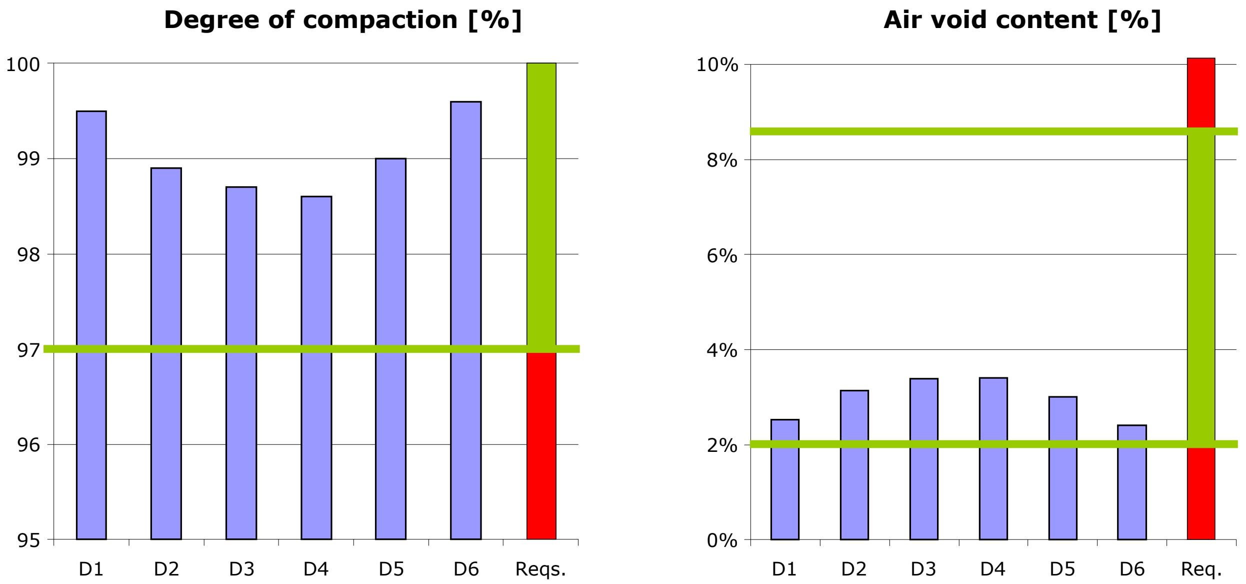

Figure 15: Results of drilling core (D1 – D6) analysis: Requirements fulfilled

No rutting after one year of service

After paving, the evenness perpendicular to the traffic direction has been determined. One year after construction the rut depth was measured again. From these measurements it can be seen that the rut depth slightly increased from 0 – 2 mm (some rut areas up to 3 mm) to 1 – 2 mm (some rut areas up to 4 mm). Hence, during the first year no degradation of the road surface occurred.

CONCLUSION – WARM MIX USING FOAM BITUMEN

The temperature reduced W-ecophalt® asphalt was successfully produced at 115°C significantly below normal hot mix temperatures. The complete coverage of the aggregates proves that stable foam is produced in the Ammann plug flow reactor and that the applied stress results in a good droplet break-up. Workability and mechanical properties are found to be equivalent to conventional hot mix asphalt.

As the produced warm mix asphalt shows properties equal to those of regular hot mix asphalt, we conclude that similar results can be achieved with other bitumen and raw materials. In addition to the in-situ measurements and the laboratory test, field observation after one year of service show that no exceptional rutting occurred. Foam bitumen is on the way to become a proven ecological alternative to conventional hot mix asphalt.

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