# Production and durability of cold mix asphalt

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Digital Object Identifier (DOI): dx.doi.org/10.14311/EE.2016.074

## ABSTRACT

*In the nineties research started with the aim to develop robust technologies, allowing production of asphalt at ambient temperature. Such technologies results in significantly lower energy consumption and carbon emissions during asphalt production. The technology investigated and discussed here is based on gentle addition of bitumen-emulsion to aggregates, followed by controlled breaking of the emulsion on the road. However, despite some early success with a number of roads installed using emulsion based cold mix asphalt the market development of such materials failed to progress. Interest was also lost due to a significant drop in energy costs in the end of the nineties.*

*In 2012 the Swedish road authority started an industry project to improve the understanding of cold mix design, production and performance and demonstrate the benefits of the technology on heavily trafficked roads. A strong relationship was found between surface area, chemical composition of stone aggregates and breaking rate of emulsions. This understanding has the potential to significantly improve the ability to design asphalt mixes that will be easy to produce and lay. Heavily trafficked test roads have been produced in the last two years with cold mixture asphalt as the base course.*

*Further, durability data from roads produced fifteen years ago will be presented. It can visually be seen that the roads have survived over the years without any significant signs of aging. Analysis of the binders confirms that age hardening over time is limited, indicating the bitumen ages slowly in the road despite of high void contents.*

**Keywords:** Cold Asphalt, Durability, Emulsions, Energy saving, Life cycle assessment

## 1. INTRODUCTION

A great effort is made around the world to minimize energy consumption in modern society and to lower the emission of carbon-dioxide ($CO_2$). Hot mix asphalt manufacture is very energy intensive especially when it comes to heating and drying aggregates [1-2]. Thus, there is a strong driver to lower manufacturing temperatures during asphalt production and in recent years a lot of effort has gone into developing novel techniques to reduce energy consumption during production [3]. Warm mix asphalt is an excellent example of how the asphalt industry has found better technical solutions, however the best way of maximizing energy saving and carbon reduction would be to make asphalt cold i.e. at ambient temperature.

One way to produce asphalt at ambient temperatures is by adding bitumen to the stone material in the form of an emulsion [4]. In this paper the use of emulsions for producing asphalts are described. Bitumen is emulsified in water using surfactants and the bitumen-emulsion is used to coat the stone surfaces prior to breaking to leave a bitumen bound asphalt material. The success of the concept is very much depending on the breaking rate of the emulsion. Ideally, the rate of breaking should be slow enough for asphalt to be produced and transported to the laying site before stiffness starts to build up, while the emulsion should commence the breaking process during compaction and continue to break rapidly on the road site once compaction is complete. It can however be difficult to predict the rate of breaking of an emulsion as it is very much dependent on the mineral type and mix gradation chosen. The rate of breaking of an emulsion is most likely dependent on the nature of the aggregate surface such as the specific surface area combined with mineral type. The work described in this paper has very much been focusing on developing a practical understanding about the relationship between emulsion breaking rate, aggregate type and actual workability of the asphalt.

Environmental impact can be described as the energy consumption during production of a road and the number of maintenance interventions during its lifetime relating to its durability over time. In this paper energy reductions will be discussed in terms of reduction of carbon dioxide release as well as energy consumption during production and paving. For calculations a program developed by the Swedish road authority [5] was used. It was found that there is a clear advantage, from an energy consumption and $CO_2$-release point of view, to choose cold mix ahead of hot mix. Further, the durability of cold laid asphalt roads has been assessed after fifteen years of service. One critical point when producing cold mix asphalt is the need to manage the excess water from the emulsion. A high void content is known to reduce life expectancy of the asphalt [1]. In spite of this data in this paper shows that there are no real signs of deterioration of cold laid asphalt roads with high voids 15 years after laying.

The aim of this paper is to describe the cold mix technology being used in Sweden and to show the benefits in terms of environmental impact. Cold technology is shown to be a sustainable option that can be used to produce roads with a high durability over time.

## 2. THE TECHNIQUE

### 2.1 Bitumen emulsions

Bitumen is dispersed in water by using a mill and adding emulsifiers where the emulsifier is acting as a bridge between two immiscible phases, bitumen and water. During asphalt-production the bitumen-emulsion breaks in contact with stone minerals leaving the bitumen covering the stones. A lot of effort has gone into trying to understand the breaking mechanism [7] and Fig. 1 is showing a hypothesis of how it may occur. The speed of breaking increases during asphalt compaction. The emulsion used for cold technology is a slow breaking cationic type (C65B5 - EN13808:2013).

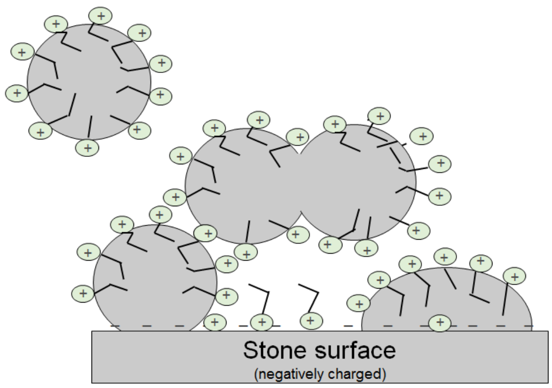


**Figure 1: Illustration of how bitumen droplets are destabilised upon contact with stone surface**

**2.2 Technical challenges and solutions**
To achieve high quality asphalt, bitumen content normally needs to be between 3 and 6 wt-% depending on the type of asphalt being produced. As bitumen is added to aggregates in the form of an emulsion that only contains 65% bitumen, the water needs to have somewhere to go when the emulsion breaks. Hence, the asphalt needs to have an open structure with a void content of approximately 10 % that leaves space for water to drain off. Figure 2 is showing an example of an open gradation curve (16Ö) intended as base course. In order to achieve a stable asphalt construction, it is also important to get the right proportions of aggregates together with an optimum amount of bitumen. If this is correctly done an extremely strong and durable asphalt is obtained that can sustain heavy loads for years.

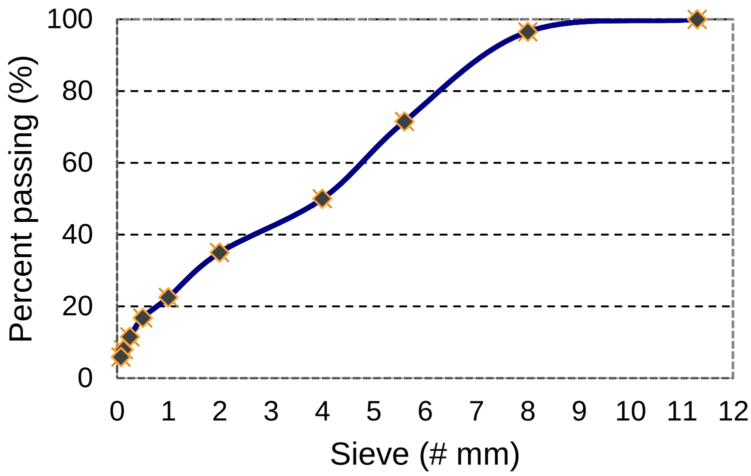


**Figure 2: Aggregate gradation with more voids than the normal dense gradations used for hot mixture asphalt**

One method aimed at improving the durability of asphalt is to ensure that the bitumen layers around the aggregates are thick enough. Covering stones surfaces sufficiently without emulsion running off is a challenge when bitumen is added as an emulsion [7, 8]. This is especially challenging when there are small amounts of fines in a mixture as is the case with the aggregate gradation pictured in Fig. 2. To overcome this problem a thickener has been added to the emulsion.

**2.3 Asphalt production**
During asphalt production the emulsion starts to break upon contact with aggregate surfaces. It is important to avoid too rapid breaking as stiffness starts to build up during breaking. This will reduce workability of the asphalt, making it difficult to lay and compact. In this application the emulsion has been designed to break during compaction and many mixers would put too much energy into the blending process, resulting in pre-mature break of the emulsion. The use of gentle mixing is critical and a special free fall blender is applied (Fig.3).

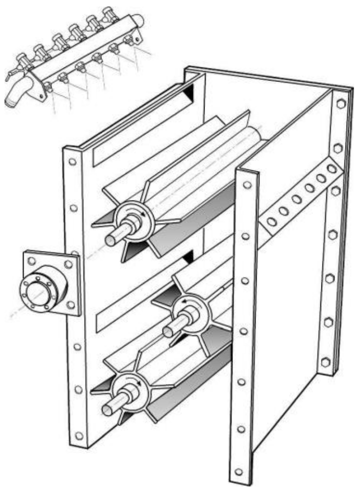

**Figure 3: Picture of a free fall blender**

In a free fall blender like the one shown in Fig. 3 bitumen-emulsion is sprayed onto the aggregates falling by gravity and the mixture is gently blended while passing through the slowly rotating paddles [9]. After blending the cold asphalt mixture is transported to the road site, laid and compacted.

**2.4 Controlling the breaking rate**

The key to a successful paving is that the emulsion does not start to break properly until compaction starts. In spite of adapting careful mixture design as well as applying gentle mixing during full scale production it has been found that in certain cases the breaking rate of emulsion against aggregates was extremely fast, resulting in stiffness build-up and poor workability. It was recognised that this was due to the inability of predicting breaking rate properly. To better understand this, a number of granite aggregates from different quarries around Sweden were gathered and tested for workability. Values were developed to assess workability and how quickly stiffness built up in mixtures during hand-mixing. A rating of 5 is suitably slow while below 3 is too fast. In addition visual assessments were made, such as if the mixture was foaming (Yes in the table). Mixtures that were still workable after five minutes and that showed foaming were regarded good and likely to be easy to blend and handle in full scale production. Breaking rate was checked after 12 hours where a rating of 5 was regarded fast and 1 slow. In this case a rating of 3 was regarded the best and likely to result in a good curing rate on the road. In an effort to better understand differences between aggregates from the various quarries and what might affect the breaking rate of emulsions, testing on the aggregates was undertaken. The emulsifier used for making bitumen-emulsion is usually an amine-type and the aim was to try to identify anything in the aggregates that might be particularly reactive to amines and thus causing rapid breaking of emulsions. Reactive siliceous aggregates [11] were thought to be one risk factor for rapid breaking to occur and in particular mylonite, which is a mineral-type that is alkali silica reactive. Petrographic analysis (SS EN 932-3) was undertaken and alkali silica reactivity (ASR) of the studied aggregates was measured and is reported in table 1. Specific surface area of the fine aggregates (fraction: 0-2 mm) was measured by gas adsorption (ISO 9277-2010). In addition water sensitivity to fines was measured by the shaking abrasion test. Key findings correlating breaking rate and curing of emulsion to surface area of the aggregate, ASR-number and water sensitivity are reported in Table 1.

**Table 1: Workability versus properties of aggregates**

| Quarry name | | Supartallen | Sälgsjön | | Råsta | |
|---|---|---|---|---|---|---|
| Petrographic analysis | Primary mineral type and wt% | Granite 96.4% | Grey/red granite 79.3 % Pegmatite 12.5 % | | Pegmatite 45.6 % Greywacke 45.1 % | |
| | Secondary mineral type and wt% | Pegmatite 3,6% | Volcanite 5.1 % Quartz 2.3 % Mylonite 0.8 % | | Alnöite 4.4 % Mylonite 3.5 % Skarn 1,4 % | |
| Water content (%) | | 2.5 | 2.5 | 3.5 | 2.5 | 3.5 |
| Workability | 1 minute | 5 | 4 | 5 | 4 | 5 |
| | 3 minutes | 5 | 3 | 4 | 3 | 3 |
| | 5 minutes | 5 | 2 | 3 | 2 | 2 |
| Foaming | | Yes | No | Yes | No | No |
| Breaking rate | 2-6 hours | 2 | 3 | 3 | 5 | 5 |
| | 12 hours | 3 | 5 | 5 | 5 | 5 |
| ASR-number | | 0 | 3 | | 48 | |
| Specific surface area ($m^2/kg$) | | 1581 | 2259 | | 3180 | |
| Water sensitivity | Swell (%) | 1.1 | 1.4 | | 3.5 | |
| | Weight loss (%) | 8.1 | 18.7 | | 29 | |

Interestingly enough it was found that the aggregates that showed highest reactivity to emulsions consisted of material with high surface area as well as high ASR number. Maybe even more interestingly these aggregates had a high sensitivity to water as seen in the water sensitivity test. Further, studies showed that by removing the fine material from gradations with highly reactive aggregates the breaking rate of the emulsion could be slowed down.

The knowledge from above has recently been used for choosing material from suitable quarries and a test road was successfully paved in 2012. The road had AADT: 3000 (11 % heavy traffic) and is situated close to Boliden in the north of Sweden.

## 3. ENERGY CONSUMPTION DURING PRODUCTION AND PAVING

The Road Authority in Sweden has developed a calculation tool called EKA [6] in which energy consumption and carbon dioxide emissions during production and paving are calculated. In the model, energy consumption for the different production steps is taken from the producer's assessment of each stage, data about raw material like bitumen and bitumen emulsions comes from Eurobitume, consumption of fuel during transportation and production is taken from actual measurements during production.

For the latest full scale trial undertaken using cold technology (in Boliden, 2012), the energy consumption and carbon dioxide emissions during production and paving was calculated using EKA. In the analysis base courses 0-22 mm (AG22) manufactured both hot and cold were compared.

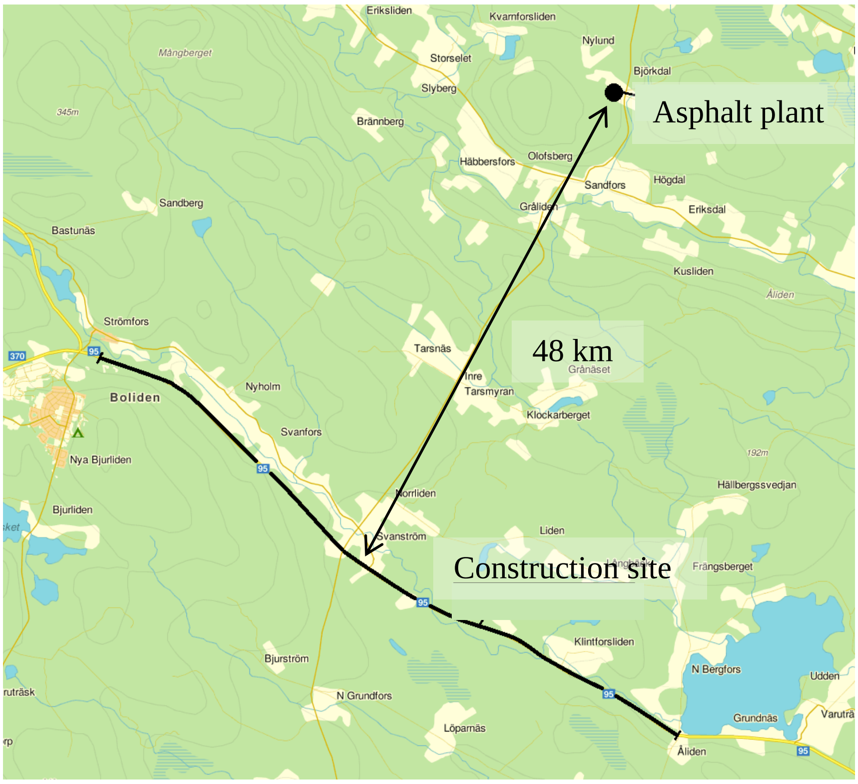


**Figure 4: Map showing the construction site in relation to the location of the asphalt plant**

The production process for hot and cold mix asphalt differs when it comes to how the asphalt is made and the assumptions described below were made:
Hot mix asphalt (150-160 °C)

- The asphalt plant is in Björkdal, while the laying site is in Skelleftehamn and the asphalt is transported 48 km.
- Diesel/heating oil was used for heating aggregates etc in the asphalt plant and electricity was used to run the plant.

Cold mix asphalt (25°C)

- A mobile asphalt plant was used and it was placed in Björkdal, also this resulting in transportation of asphalt for 48 km.
- Electricity was produced with a diesel generator.

The quarry is located in Björkdal and to obtain aggregates the land has to be cleared and the rocks drilled and blasted (explosives had to be transported 171 km from Umeå). The total diesel consumption was 1094 liter and it generated 0.2 kg $CO_2$/ton aggregate and an energy consumption of 33.5 kWh/ton. The aggregates was then handled and crushed to desired fractions. The crushing consumed 7755 liter diesel and it generated 1.3 kg $CO_2$/ton aggregate and an energy consumption of 5.1 kWh/ton.

Asphalt from the old road was recycled and added to the new asphalt in both cases (hot as well as cold manufacture). The old asphalt had been milled and transported 20 km from the road to the asphalt plant. The hot mixture asphalt was produced in a traditional plant while a mobile free fall blender was used for the cold technology. The bitumen for hot mixture was transported 182 km from Holmsund to Björkdal and the bitumen for cold technology was transported 92 km from Piteå to Björkdal. The release of $CO_2$ during the production of hot mixture is 35.5 kg $CO_2$/ton asphalt while corresponding value for cold mix is only 7.1 $CO_2$/ton asphalt. Similarly energy consumption is 132.3 kWh/ton vs 37.4 kWh/ton.

In Table 2 the various production steps are listed together with the carbon dioxide release and energy consumption associated with them. The paving process is the same for both types of asphalts and there are no major differences between the two types. It can be seen that most of the energy is saved during the asphalt manufacturing step when choosing cold technology.

**Table 2: Summary of amount $CO_2$ released and energy consumption**

| Activity | Hot mix AG22 | | Cold mix AG22 | |
|---|---|---|---|---|
| | **kg $CO_2$/ton asphalt** | **kWh/ton asphalt** | **kg $CO_2$/ton asphalt** | **kWh/ton asphalt** |
| Extraction and crushing of rocks | 1.5 | 38.6 | 1.5 | 38.6 |
| Asphalt manufacture | 35.5 | 132.3 | 7.1 | 37.4 |
| Transport and paving | 5.3 | 20.2 | 5.1 | 19.5 |
| **Total** | 42.3 | 191.1 | 13.7 | 95.5 |
| | **kg $CO_2$ / $m^2$** | **kWh / $m^2$** | **kg $CO_2$ / $m^2$** | **kWh / $m^2$** |
| **Total** | 5.5 | 24.6 | 2.0 | 12.8 |

The table shows that there are significant differences in energy consumption and carbon dioxide release during manufacturing and paving when comparing the hot and cold alternatives. It can be seen that by choosing cold mix asphalt carbon dioxide release as well as energy consumption from the manufacture and paving process can be halved.

## 4. DURABILITY

### 4.1 Test conditions

During the nineties road trials were made in the north of Sweden where temperatures span between -30 °C in the winter and + 30 °C in the summer time. The temperature variations put a lot of stress on the bitumen but fifteen years later the roads were still in good condition [12]. Thus, in 2012 field cores were taken from a few selected roads. Stiffness modulus or indirect tensile strength (ITS) was determined using EN 12697-26. The air void content was determined in accordance with EN 12697-8. Bitumen was recovered from cores using a standard procedure similar to EN 12697-3 and dichloromethane was used to extract bitumen from the asphalt mixture. Recovered bitumen was tested for penetration (PEN) using EN 1426 and softening point (R&B) using EN1427.

### 4.2 Evaluation of an old road in Trinnan

A secondary road (AADT of 200) was paved in Trinnan in the north of Sweden in 1997. 50-60 mm of cold mix asphalt was put on top of a road-base of soft sand. The residual bitumen content was approximately 5,5 % and initial PEN 330/430. Over the years, drill cores has been taken from the road and Figure 5 is showing the change in penetration and softening point over time as measured on bitumen recovered from cores. Stiffness modulus of the asphalt mixtures are reported for year 2 and year 15. PEN after two years was not measured but is calculated from softening point to about 280 mm/10.

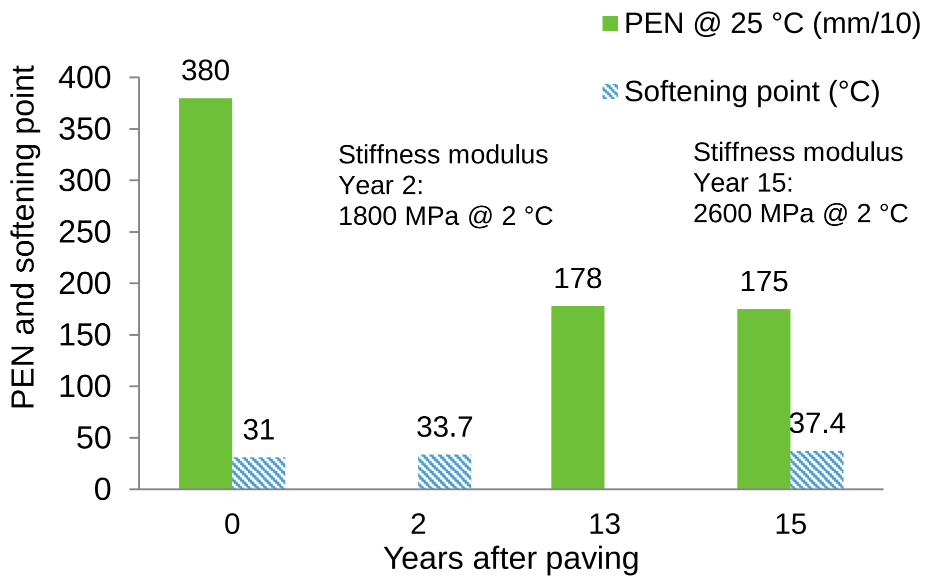


**Figure 5: Change in penetration and softening point over time**

It can be concluded that the bitumen show surprisingly little age hardening after fifteen years. Also visual inspection of the road confirms that the roads are still in excellent condition.

**4.3 Överboda**

A small rural road was paved in Överboda also in the north of Sweden in 1998. The AADT is 200 of which 35 is heavy loaded trucks. The road was then monitored over time and final evaluation was made in 2012. Field cores were taken and the recovered bitumen was analysed. The results are reported in Fig. 6 where the graph to the left is recovered bitumen with initial PEN of 190 and the graph to the right is recovered bitumen with an initial PEN of 380.

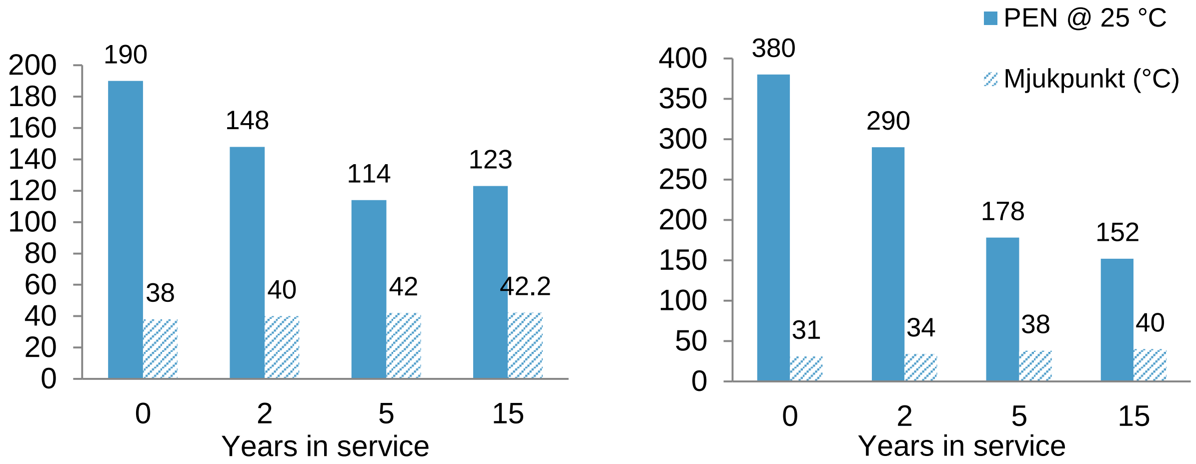


**Figure 6: Change in PEN and softening point over time**

It can be seen that the softer bitumen hardens more than the one with initial PEN of 190 over 15 years while the rate of hardening is similar for both during the first two years. In both cases the bitumen are still good after 15 years in the road. Visual inspection of the road revealed a few low temperature cracks which had partly healed.

The change in stiffness modulus/ITS was tested on cores taken from the road over the years and are reported in Table 3. As can be seen from the table the stiffness modulus is initially low and builds up slowly. Initial build-up is highest during the first two years.

**Table 3: Stiffness modulus tested on field cores taken over the years**

| Years in service | Stiffness modulus @ 2 °C (MPa) | |
|---|---|---|
| | Initial PEN of 190 | Initial PEN of 380 |
| 0 | 1450 | 750 |
| 2 | 2700 | 1450 |
| 5 | 4600 | 1700 |
| 15 | 4000 | 3500 |

**4.4 Aging in relation to high void content**

High level of air voids in asphalt is known to shorten the life-time of bitumen, which is seen as a lowering of PEN over time [1]. The void content in the cold mixture asphalt was somewhere around 10-12 % and it was surprising that the asphalt was in a good condition after 15 years of service. To put this in relation retained PEN (PEN of the bitumen after a number of years in service divided with PEN of original bitumen) has been plotted against void content in Fig. 7. These numbers where then compared to void content in hot mixture asphalt [13].

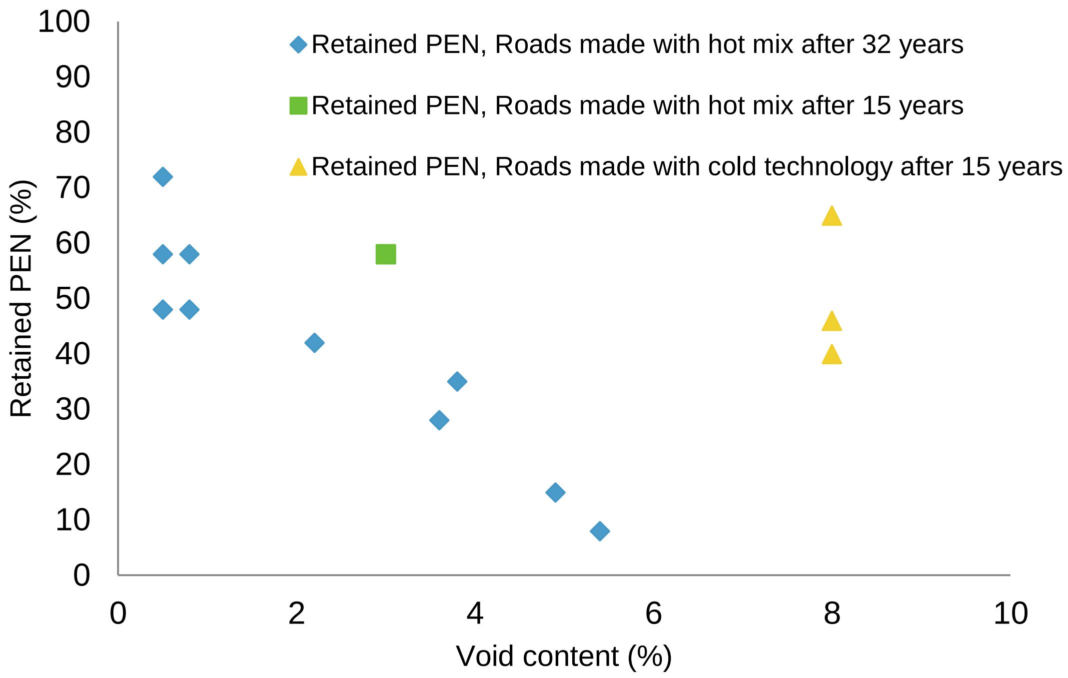


**Figure 7: Retained PEN of bitumen as a function of asphalt air voids after 15 and 32 years**

As can be seen from Fig. 7 the retained PEN is remarkably high for the bitumen extracted from cores from roads made with cold technology as compared to those made with hot asphalt and lower void content. One may argue that the reason why the bitumen treated cold sustained well over time is an effect of the cool climate in the north of Sweden and the low traffic volumes on the roads made with cold technology. However, it should be noted that one reason that the data cannot be compared properly is that there are no data available for hot mixture asphalt with initial void content of 10-12 %. This is most likely due to the fact such asphalt would not survive 15 years in service in Sweden. In this context it is interesting to note that the short-term aging of asphalt made hot is severe, while the cold mix asphalt is not at all exposed to a heating step and this type of aging [1].

In an effort to compare properties of bitumen extracted from cores, virgin bitumens were exposed to standard lab aging. In the strategic highways research program (SHRP) Superpave binder specification a sequence of Rolling Thin Film Oven Test (RTFOT) followed by pressure aging vessel (PAV) is used for simulating long-term in-service ageing [3]. PAV was run at an air-pressure of 2070 kPa at 100 °C for 20 hours in this study. As there is no hot mixing step when preparing cold mix asphalt, PAV testing only was used with the aim to simulate long-term aging for cold asphalt pavement. In Table 4 retained PEN and softening point for fresh and laboratory aged bitumen are compared with those on bitumen recovered from cores from 15 year old cold mix roads.

**Table 4: Retained PEN and softening point for unaged, lab-aged and recovered bitumen**

| | **PEN 190** | | **PEN 380** | |
|---|---|---|---|---|
| | **Retained PEN (%)** | **Softening Point (°C)** | **Retained PEN (%)** | **Softening Point (°C)** |
| Unaged | 100 | 38 | 100 | 31 |
| After RTFOT and PAV | 35 | 50 | - | - |
| After PAV | 49 | 48 | 42 | 42 |
| Recovered | 65 | 42 | 48 | 39 |

As can be seen from the data in Table 4 the best values on retained PEN and R&B were measured for bitumens extracted from field cores. All lab-aged samples showed worse values independent of the tests chosen. Given that the lab methods simulate reality, one may speculate that the reason for the bitumen in the road sustaining well over time (in spite of high void contents) is the mild handling of the bitumen at ambient temperature during production, possibly in combination with the relatively cold climate in Umeå and low traffic volumes.

## 5. CONCLUSIONS

Cold technology is an environmentally friendly option to prepare asphalt by adding bitumen in the form of an emulsion. One challenge has been to improve the ability to predict breaking rate of emulsion when doing mixture design. A strong relationship was found between surface area, mineral type and breaking rate of emulsions. This understanding has the potential to significantly improve the ability to predict and design asphalt mixtures that will be easy to produce and lay. For example it is now possible to exclude fine material from quarries that consists of minerals that speed up the breaking rate of emulsions.

The asphalt made with cold technology was seen to have a high durability. In spite of high void content in the asphalt, which is usually considered to make the asphalt susceptible to aging as well as cracking, the road surfaces were in remarkably good condition and very few cracks could be noticed even 15 years after paving. Further, recovered bitumen still showed good PEN and R&B values after 15 years in service.

It was found that energy consumption as well as carbon dioxide release during manufacturing and paving could be halved by choosing cold technology rather than making asphalt hot. This combined with the high durability observed makes it a very attractive option from an environmental point of view.

The biggest challenge in Sweden moving forward is to prove that cold technology is also suitable for roads with higher traffic.

## ACKNOWLEDGMENTS

Örjan Otterström is thanked for extracting all the bitumen from cores from old roads. Ulf Lillbroända, Lars-Åke Holmgren and Lena Thunell are thanked for driving the technical work forward over the years. Xiaohu Lu is thanked for the valuable discussions around aging of roads. Dennis Day and Safwat Said are acknowledged for their valuable comments during the writing of this paper. Hilde Soenen and Helene Odelius are thanked for continuous feedback and support.

## REFEERENCES

[1] Shell bitumen handbook 5th Edition, Read, J., Whiteoak, D., Thomas Telford Publishing, 2003

[2] Industrial Energy Efficiency Accelerator, Guide to the Asphalt Sector, Carbon Trust

[3] Sustainable Asphalt Pavements: Technologies, Knowledge Gaps and Opportunities, Miller, T.D., Bahia, H.U., Prepared for the Modified Asphalt Research Centre, Feb, 2009

[4] Bitumen emulsions, Redelius, P., Walter, J., Emulsion and Emulsions Stability Surfactant Series 61 CRC Press, p. 383-413, 2005

[5] Kalltillverkad asfaltbeläggning, Said, S., Jacobson, T., VTI-rapport 865-2015, 2015

[6] Energieffektiva asfaltbeläggningar, Martinsson, K., Transportforum, Linköping, January 2014

[7] Bitumen emulsions, Pink Art Ltd, ISBN 2-913414-49-4, 2008

[8] Breaking control of bitumen emulsions, Redelius, P., 5th Eurobitume Congress, Stockholm 16-18 June 1993, Vol. 1A p. 353-357

[9] A novel system for delayed breaking control of bitumen emulsion, Redelius, P., 1.st World Congress on Emulsions, Paris, Oct 19-22, 1993 Vol 1, Paper 122 147

[10] The new cold mix technique, recycling and virgin cold-mix production, Lillbroända U., Lundberg, R., Wiklund, M., Olsson, K., Redelius, P., Third World Congress on Emulsions 24-27 Sep 2002, Lyon France

[11] Alkalisilika reaktioner i svensk betong, CBI Rapport 4:92, Lagerblad, B., Trägårdh, J., 1992

[12] Field experience of cold mix asphalt, Redelius, P., Östlund, J-A, Soenen, H. Road Materials and Pavement design, In press

[13] Material characteristics of long lasting asphalt pavements, Lu, X., Redelius, P., Soenen, H., Thau, M., Road Materials and Pavement Design, p. 567-585, Vol. 12, No. 3, 2011