Warm Mix Asphalt for Cold Weather Paving

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16. ABSTRACT

Increased environmental awareness and stricter emissions regulations have led to a development of warm mix asphalt (WMA) to reduce the high mixing temperatures of regular hot mix asphalt (HMA). Its benefits are reduction in energy consumption during production and reduced emissions during production and placement. The three most tested methods are; WAM Foam, Aspha-min zeolite and Sasobit wax. All three methods reduce the viscosity of the binder at a certain temperature range, allowing the aggregate to be fully coated at lower temperatures than in HMA production.

Previous research has not focused much on how WMA functions in cold weather paving. This paper investigates WMA's potential in cold weather conditions and specifically how Iceland, with such conditions, can benefit from it. The conclusions in this paper are drawn from a literature review and a survey that was conducted among Iceland's paving industry professionals.

Reduced emissions are especially beneficial in densely populated areas and in non-open air paving. The decreased viscosity allows effective compaction at lower temperatures where cool down rates are slower. WMA's disadvantages are mainly related to rutting and moisture susceptibility issues. Using WMA processes at HMA production temperatures: 1) Increases the temperature gap between production and cessation, allowing e.g. increased haul distances 2) Facilitates compaction, which is beneficial for; stiff mixes and RAP, paving during extreme weather conditions and reduction in compaction effort.

Icelandic professionals are generally positive towards WMA, interested in testing it further for Icelandic conditions, and hopeful about its potential for helping with some key problems in Icelandic paving. The final conclusion is that WMA is a viable option for cold weather conditions and for the paving industry in Iceland, Sasobit is most suitable of the three methods, and usage incentives are twofold: 1) As a compaction aid for mixes produced at, or close to, regular HMA production temperatures, used to increase haul distances and/or pave during cold and difficult weather conditions, and sometimes slightly reduce fuel consumption as well. 2) As an environmentally friendly method when emissions approach limits, although not an issue today it may become one with stricter emissions regulations or increased production.

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Abstract

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1. INTRODUCTION

Environmental awareness has been increasing rapidly over the past years. Extensive measures like air pollution reduction targets set by the European Union with the Kyoto protocol have encouraged efforts to reduce pollution.

Warm Mix Asphalt (WMA), a new paving technology that originated in Europe, is one of those efforts. It allows a reduction in the temperatures at which asphalt mixes are produced and placed. Its benefits are reduction in energy consumption and reduced emissions from burning fuels, fumes and odors generated at the production plant and the paving site. This paper investigates the potential use of warm mix asphalt in cold weather conditions and specifically how countries like Iceland, with such conditions, can benefit from this technology. Early research and marketing efforts have mainly focused on the environmental benefits and the reduced energy consumption of the technology and not as much on how it functions in cold weather paving.

The primary objective of this research is to find out whether warm mix asphalt is a viable option for the paving industry in Iceland. In the process of answering that question, warm mix asphalt's advantages and disadvantages compared to traditional hot mix asphalt (HMA) are explored and the question of whether warm mix asphalt is a viable paving option for cold weather conditions in general is also answered. The conclusions of this paper are primarily drawn from a literature review that was conducted on warm mix asphalt to evaluate what is known about its performance and a survey that was conducted in Iceland by sending a questionnaire to professionals in the industry. Conditions and paving practices in Iceland are also explored to give an understanding of common paving issues in Iceland. Hopefully this paper can assist potential warm mix asphalt users in cold weather regions to understand the basic differences in the available methods and how they are differently suitable for the different situations that can come up in cold weather paving.

2. BACKGROUND

2.1 HISTORY OF WARM MIX ASPHALT

The discussion of lowering the heat used to produce asphalt mixes is not new. The idea of saving energy and lowering emissions in the asphalt industry has been discussed for decades.

In 1956, Dr. Ladis H. Csanyi, a professor at Iowa State University, realized the potential of foamed bitumen for use as a soil binder. Since then, foamed asphalt technology, which allows lower mixing temperatures, has been used successfully in many countries. The original process consisted of injecting steam into hot bitumen. In 1968, Mobil Oil Australia, which had acquired the patent rights for Csanyi's invention, modified the original process by adding cold water rather than steam into the hot bitumen. The bitumen foaming process then became more practical. *[1]*

In 1994, Maccarone examined developments in cold mixed asphalt based on the use of foamed bitumen and very high binder content emulsions. He wrote that around the world the use of cold mixes for use on roadworks are gaining greater acceptance. Such systems are energy efficient and environmentally friendly. Cold mixes do not emit hydrocarbons and use less fuel in manufacturing. *[2]*

Despite many good properties, cold mixes have not affected hot mix asphalt's position as the primary road surfacing material because they have not achieved the same overall long-term performance as hot mixes.

In 1999, Jenkins et al. introduced a new process, half-warm foamed bitumen treatment. Their paper explores the considerations and possible benefits of heating a wide variety of aggregates to temperatures above ambient but below 100°C before the application of foamed bitumen. *[3]*

A warm asphalt mix process (WAM) has been developed in Europe and was reported by Harrison and Christodulaki at the First International Conference of Asphalt Pavements in Sydney, 2000. A more complete report was given by Koenders et al. at the Eurobitume congress in 2000. *[4]* Their paper describes an innovative warm mixture process that was tested in the laboratory and evaluated in large-scale field trials (in Norway, the UK and the Netherlands) with particular reference to the production and laying of dense graded wearing courses. *[5]* Their work resulted in the development of WAM Foam, Warm Asphalt Mix with foamed bitumen. *[6]*

At the Eurobitume congress in 2004, Barthel et al. introduced the use of a synthetic zeolite additive to produce warm mix asphalt. The zeolite creates a foaming effect that results in a higher workability of the mix. *[7]*

Warm mixes have received some attention in Europe and Australia since around 2000. The pavement industry in North America started to give warm mixes some interest a few years later and in June 2005 the National Center for Asphalt Technology (NCAT) published two reports about the use of Sasobit, a synthetic wax, and Aspha-min, a synthetic zeolite, in warm mix asphalt. *[8,9]*

2.2 Potential Warm Mix Asphalt Benefits

In the following sections, the benefits that are usually publicized in literature as WMA's main benefits and issues are briefly discussed. These are the emissions reductions, reduced energy consumption and decreased viscosity.

2.2.1 Energy Consumption

The reduction in energy consumption is the most obvious benefit of WMA and is generally marketed and discussed in literature as one of the two main benefits of WMA. Studies have shown that energy consumption reductions of about 30% can be achieved by lowering the production temperatures at the asphalt plant. The reduction in energy consumption reduces the cost of the asphalt production but there can also be an added cost involved in using the WMA process, i.e. for additives and/or equipment modification. How much that additional cost is depends on the WMA method used. Another side benefit of the reduction in production temperatures sometimes mentioned is less wear and tear of the asphalt plant. *[10]*

2.2.2 Emissions

The other main benefit of WMA is the reduced emissions because of the reduced production temperatures. According to literature, WMA production significantly reduces emissions, fumes and odor compared to a regular HMA production. Emissions from asphalt production and placement can, at certain elevated levels, be harmful to health.

In 2000, the National Institute for Occupational Safety and Health (NIOSH) in USA published a hazard review on Health Effects of Occupational Exposure to Asphalt. *[11]* In this review, NIOSH evaluated the potential health effects of occupational exposure to asphalt. In 1977, NIOSH determined the principle adverse health effects to be irritation of membranes of the conjunctivae and the respiratory tract. NIOSH also acknowledged that evidence from animal studies indicated that asphalt left on the skin for long periods of time could result in local carcinomas. On the basis of this evidence, NIOSH recommended the following exposure limit (REL):

> "NIOSH recommends minimizing possible acute or chronic health effects from exposure to asphalt, asphalt fumes and vapors, and asphalt-based paints by adhering to the current NIOSH REL of 5 mg/m^3 [measured as total particulates] during any 15 min period and by implementing the following practices:
>
> - Prevent dermal exposure.
> - Keep the application temperature of heated asphalt as low as possible.
> - Use engineering controls and good work practices at all work sites to minimize worker exposure to asphalt fumes and asphalt-based paint aerosols.
> - Use appropriate respiratory protection." *[11, pg. 96]*

In 1988, NIOSH recommended that asphalt fumes also be considered a potential occupational carcinogen. Since then, additional data have become available from studies of animals and humans exposed to asphalt. A direct quote from the main findings of the hazard review from 2000 follows:

> "The findings of this hazard review continue to support the assessment of the 1977 NIOSH criteria document on asphalt fumes, which associated exposure to asphalt fumes from roofing, paving, and other uses of asphalt with irritation of the eyes, nose, and throat. Furthermore, in studies conducted since the[n] […] these symptoms have also been noted among workers exposed to asphalt fumes at geometric mean concentrations generally below 1 mg/m^3 total particulates and 0.3 mg/m^3 benzene-soluble or carbon disulfide-soluble

> particulates, calculated as a full-shift TWA [time-weighted average]. Recent studies also report evidence of acute lower respiratory tract symptoms among workers exposed to asphalt fumes." *[11, pg. 94]*

> Conclusions regarding potential carcinogenicity of paving asphalt fumes were:
>
> "Data regarding the potential carcinogenicity of paving asphalt fumes in humans are limited. […] Although genotoxicity assays using laboratory-generated and field-generated fumes have been conducted, only the laboratory-generated fumes were genotoxic. Therefore, NIOSH concludes that the collective data currently available from studies on paving asphalt provide insufficient evidence for an association between lung cancer and exposure to asphalt fumes during paving. The available data, however, do not preclude a carcinogenic risk from asphalt fumes generated during paving operations." *[11, pg. 95]*

A discussion about the possible risk of cancer at other sites than lungs mentions that a few studies have reported an association between cancers at sites other than lungs and occupations having the potential for exposures to asphalt, but concludes by saying:

> "Because of lack of consistency among studies and issues of the confounding effects of other substances, the evidence for an association between exposure to asphalt and non-respiratory cancers is weak and requires further confirmation [...]" *[11, pg. 75]*

It is also mentioned in the hazard review that positive mutagenic responses obtained from animal studies using laboratory-generated paving asphalt fumes are a cause for concern and support the need for further research. *[11, pg. 87]*

The NIOSH hazard review also reports a study conducted in 1993 where fumes were collected from a storage tank at a hot mix plant at a temperature of 149°C (300°F) and from a laboratory generation at temperatures of 149°C and 316°C (300°F and 601°F). The fumes were analyzed for selected PACs (Polycyclic Aromatic Compounds). The concentration of four-ring Polycyclic Aromatic Hydrocarbons (PAHs) was highest in fumes generated in the laboratory at the highest temperature. Several of the four-ring PACs are carcinogenic. These results and results from other similar studies indicate that asphalt fumes generated at high temperatures are probably more likely to generate carcinogenic PAHs than fumes generated at lower temperatures. *[11]* Although the two temperatures that are compared in this study are higher than the temperatures used for

WMA and HMA productions, this might indicate an additional advantage of the reduced emissions; i.e. it is possible that the fumes themselves become less hazardous with the decreased production temperature. This has not reportedly been examined for WMA.

2.2.3 Viscosity

The functionality of WMA technologies is based on reducing the viscosity of the asphalt binder at a certain temperature range. The reduced viscosity allows the aggregate to be fully coated at a lower temperature than what is traditionally required in HMA production. Because of the reduced viscosity, the WMA processes can work as a compaction aid and some benefits related to this are often mentioned in relation to WMA discussions, such as easier handling, extended paving season, longer haul distances and a reduction in necessary roller compaction.

3. WARM MIX ASPHALT

Several new processes and products have been developed to reduce the mixing and compaction temperatures of HMA without compromising the quality of the mixture or the resulting pavement. This section discusses the warm mix asphalt concept and a few of the different processes that have been developed.

Traditional HMA is usually produced at temperatures between 140 and 180°C (284 and 356°F) and compacted at about 80 to 160°C (175 to 320°F). The temperature of the asphalt mix has a direct effect on the viscosity of the asphalt cement binder and thus compaction. As hot mix asphalt temperature decreases, its asphalt cement binder becomes more viscous and resistant to deformation, which results in a smaller reduction in air voids for a given compactive effort. Eventually, the asphalt binder becomes stiff enough to prevent any further reduction in air voids regardless of the applied compactive effort. The temperature at which this occurs, the cessation temperature, is considered to be about 79°C (175°F) for dense graded HMA mixes. *[12]* These high temperatures for hot mix asphalt are required to achieve the right balance between:

- Low viscosity of the bitumen to obtain full aggregate coating;
- good workability during laying and compaction;
- rapid increase in mechanical strength, and;
- durability during traffic exposure. *[13]*

The goal of the WMA process is to reduce the high temperatures at which traditional asphalt mixes are produced and placed without adversely affecting these properties. Its benefits, as currently marketed and addressed in literature, are reduction in the energy consumption that is required to heat traditional HMA to temperatures above 150°C (300°F) at the production plant, and reduced emissions from burning fuels, fumes, and odors generated at the plant and the paving site. There are primarily three technologies that have been observed to produce WMA in Europe: *[5,15]*

- **WAM Foam (Warm Asphalt Mixes with Foam).** A two component binder system that introduces a soft and hard foamed binder at different stages during plant production;
- **Aspha-min zeolite.** The addition of a synthetic zeolite during mixing at the plant to create a foaming effect in the binder;
- **Sasobit wax.** The addition of a Fischer-Tropsch paraffin wax during mixing at the plant to decrease the viscosity of the mix;
- **other methods** mentioned in literature include for example Asphaltan B, a low molecular weight esterified wax, and Evotherm, a process based on a chemistry package that includes various additives.

All these technologies appear to allow the production of WMA by reducing the viscosity of the asphalt binder at a given temperature.

The three methods that have been most prominent in literature and research, WAM Foam, Aspha-min zeolite and Sasobit wax, are discussed one by one in the following three sections. The other methods, which are not as prominent, are briefly described in section 3.4.

The amount of research and type of reports that are available for the three methods varies somewhat. For the WAM Foam, the process itself is patented and it requires considerable equipment modifications. That may affect the amount of independent research conducted because no reports of independent studies were found or were pointed out by the developers. Therefore, all the information about WAM Foam is based on research conducted by the developers themselves. Although there can not be seen any specific indications of biased results or discussions in those reports, this needs to be kept in mind when evaluating the results and comparing the three WMA methods.

For both the Aspha-min zeolite and Sasobit wax methods the situation is different. More information from independent studies is available which might be because for these methods the process itself is not patented and equipment modifications are not necessary, although both methods are based on the use of patented additives. For example, the National Center for Asphalt Technology (NCAT) in the USA conducted laboratory studies on both the Aspha-min zeolite and Sasobit wax methods and reported them in

2005. Those two reports, along with a Sasobit wax performance evaluation done for the Maryland State Highway Administration, give detailed and unbiased information about various properties of the two methods.

3.1 WAM FOAM

WAM Foam (Warm Asphalt Mixes with Foam) is a patented process developed jointly by Shell Global Solutions and Kolo Veidekke in Norway. In the WAM Foam production process, two different bitumen grades, soft bitumen and hard bitumen, are combined with the mineral aggregate. This process makes it possible to produce the asphalt mixture at temperatures between 100 and 120°C (212 and 248°F) and compact it at 80 to 110°C (176 to 194°F). *[5,16]*

A WAM Foam modified asphalt plant first mixes the soft bitumen with the mineral aggregate in order to achieve pre-coating and then the foamed bitumen, i.e. the hard grade, is introduced in the second step. *[17]* The viscosity of the soft bitumen is chosen such that at temperatures below 100°C (212°F) it can fully coat the mineral aggregates (i.e. it must be less than 0.3 Pa-sec at 100°C (212°F) *[5]*). The hard component is added in the form of a foam and must have a penetration at 25°C (77°F) between 1 and 10 mm so standard penetration grades such as 10/20, 20/30, 35/50, 40/60 and 70/100 are suitable hard components. The blend ratio of the soft and hard binder components is determined by the required penetration level of the final binder. If required, an adhesion improver can be used in the binders to reduce water sensitivity. *[17]* The rate of dissolution of the hard component into the soft component is important because it determines the workability of the mixture and the initial binder composition and properties. *[5]* The thought behind this mixing procedure is to obtain a good distribution of the bitumen in the mixture and a good workability during paving. *[13]*

Studies have used dense graded asphalt mixtures but in principle the WAM Foam process is equally applicable to other asphalt mixes such as open graded and gap graded mixtures. *[5]*

Foamed bitumen is produced by injecting cold water at a level between 1 and 5% into hot bitumen. When it contacts the hot bitumen, the water turns into steam that produces a large volume of foam which slowly collapses with time and the bitumen resumes its original properties. The volume expansion ensures the bitumen is distributed evenly in the asphalt mixture and coats the aggregates.

At early stages in the development of WAM Foam, the hard bitumen added was in the form of a powder, an emulsion or foam. The use of hard bitumen powder gave good results in the laboratory but it was not considered practical to implement due to safety issues. Hard bitumen emulsions gave promising results but the use of hard bitumen foam showed good asphalt properties while not having the drawbacks that powder (safety issues) and emulsions (cost) have. *[13]*

3.1.1 The Asphalt Plant

The lower temperature operation of the aggregate dryer combined with the moisture from the foam raise a number of potential issues regarding the operations in the asphalt plant. For example, the temperature of the dryer must be above 100°C (212°F) to prevent clogging of the dust collection system. *[13]* The WAM Foam modified asphalt plants in Norway manage to operate the dryer at about 120-130°C (248-266°F) without problems with burner instabilities or in the dust collection system. To compensate for the pressure build-up in the mixer while foaming, a good air extraction system is needed. *[17]*

In a batch asphalt mixing plant the foamed bitumen is produced by injecting water into the bitumen pipe in a special nozzle system, just before the bitumen enters the mixer. The foam is produced in a discontinuous way. An airgun is used to blow the foaming chamber and pipes clean after each foam injection. The production capacity of the plant can be maintained for all types of mixtures.

The WAM Foam process is more suitable for a drum plant because then the foam can be produced in a continuous way. Insulation of pipes and the cleaning is not necessary to the same degree as in a batch plant. *[17]*

3.1.2 Laboratory Studies

A laboratory study reported by Koenders et al. in 2002 used dense WAM Foam asphalt mixtures and conventional hot mixtures for comparison (typical dense graded mixtures;

Norwegian Agb11 and Dutch DAC0/11) to determine general workability, mixture stability and abrasion resistance. The results were:

- The degree of compaction (% air voids) were measured in a gyratory compactor and the % air voids were marginally higher for the warm mixes;
- resistance to permanent deformation (dynamic creep test) was tested in the Nottingham Asphalt Tester. The test results, expressed in axial strain (%), were very similar for both types of asphalt mixtures indicating equal performance;
- a (modified) Californian abrasion test was used to assess the adhesion performance of the mixes. It is done by subjecting specimens to rapid impact of steel balls on the surface after having been submerged in water for 24 hours. The results showed very little difference in the abrasion values of WAM Foam mixtures compared with the hot mixtures. *[13]*

According to information from Kolo Veidekke, some research has been done on water sensibility issues but not much has been published yet. They tend to get somewhat lesser values in the lab, but that does not correlate to results from cores taken from the road. Visual inspections of the road do not indicate that this should be an issue. *[18]*

3.1.3 Field Trials

The first WAM Foam field trial was carried out in May 1999 in Norway, using a Midland Mix-Paver (paver and pugmill combined) modified for foaming. The whole paving operation was carried out with satisfactory results despite extreme weather conditions, even some snowfall. The second WAM Foam trial was carried out close to Oslo in Norway in May 2000 using a batch plant. *[17]*

The first larger scale road trial was carried out on the main road RV120 in Hobøl, Norway, in September 2000, where a one lift wearing course and a reference hot mix section were laid. The mixture was dense asphalt concrete Ab11 with an 85 pen (final) binder and it was produced in a batch plant. Voids contents measured along the WAM Foam and hot mix sections had exactly the same average, 3.9%. Rutting, smoothness and surface texture has been monitored two times a year and measurements from the years

2000 to 2003 show very similar results for the warm and hot mixtures. The percentage of studded tires on cars in Norway is close to 60% in the winter period and the rutting results show that the mixtures respond similarly to the first winter, when the studded tires wear off the mortar on the surface. *[17]*

In April 2001 a wearing course was laid on a section of the FV82 road in Norway, with dense asphalt concrete WAgb11 with 180 pen (final) binder and a conventional hot mixture for comparison. Void contents were slightly higher for the warm mix but still well within Norwegian specifications. Rut depth measurements carried out from 2000 to 2003 showed that the rut depths were very similar for the warm and hot mixtures. Smoothness measurements (as measured by International Roughness Index, IRI) from 2001 to 2003 gave very similar results for the warm and hot mixtures. The mean profile depth was used to evaluate skid resistance and the results were all within a range for good skid resistance.

Another trial was held in 2001 in the UK, where a WAM Foam 20 mm (0.78 in) Dense Road Basecourse (DRB) with an equivalent of a 40/60 pen bitumen and a conventional hot 20 mm (0.78 in) DRB with 40/60 pen were manufactured and paved. The texture of the warm asphalt mixture was identical to the hot mixture and the stiffness modulus was identical also. Fatigue measurements showed that statistically the fatigue properties are the same. Those three field trials are summarized in the following table.

Table 3.1: A summary of the WAM Foam field trials discussed in the text.

Location	RV120, Norway	FV82, Norway	UK
Date	September 2000	2001	April 2001
Type of mix	Dense asphalt concrete Ab11 with a 85 pen (final) binder	Dense asphalt concrete WAgb11 with a 180 pen (final) binder	20 mm (0.78 in) Dense Road Basecourse (DRB) with a 40/60 pen bitumen
Air voids [%], (WAM Foam compared to regular)	Identical average, 3.9%	Slightly higher for the warm mix	-
Rutting (WAM Foam compared to regular)	Marginally lower for the warm mix	Marginally higher for the warm mix	-

In 2001, productions of WAM Foam in a batch plant and a drum plant were started in Norway for normal (commercial) paving works. About 48000 tons of asphalt produced according to WAM Foam process was paved from 2000 to 2003. Different types of mixtures have been produced, dense graded and stone mastic asphalt, with different final grades and various combinations of hard and soft bitumen *[17]*

3.1.4 Environmental Benefits

On Shell's webpage, it is stated that carbon dioxide emissions are reduced to half in the WAM Foam process, and fumes emitted from the bitumen are halved for every ten degree reduction in temperature. *[6]*

As a part of Shell and Kolo Veidekke's studies on WAM Foam, the emissions at an asphalt production plant were measured and compared to a hot mix production. Fume emissions, both organic and inorganic parts were determined as Total Particulate Matter (TPM). The organic part, known as Benzene Soluble Matter (BSM) was also determined. Bitumen and their fumes contain traces of Polycyclic Aromatic Compounds (PAC) originating from the crude oil. Some of these compounds are irritants and other are suspected to have carcinogenic properties. Attention was also given to PAC's in the gas phase, called Semi-Volatiles (SV). Table 3.2 shows the measurement results. The final result is that the fume emission during warm mixture production is negligible compared to the emission during hot mixture production. The results are said to be fully comparable since weather conditions were constant during both productions. *[19]*

Table 3.2: Results from emissions measurements for a WAM Foam production and a regular HMA production.

	Mix temperature [°C (°F)]	BSM emissions [mg/m^3]	PAC emissions [ng/m^3]	TPM emissions [mg/m^3]
HMA production	165 (329)	0.2 and 0.5	38 and 119	1.2 and 0.93
WAM Foam production	115 (239)	≤ 0.05 (below a 0.05 mg/m^3 detection level)	4.9 and 2.5 (similar to the background static samplers (1.9))	0.09 and neg.*

* Low TPM results are often inaccurate due to loss of fibers during disassembly and give an underestimation of the results or may even give negative values as was the case for one of the

warm mixture samples. Despite this, it is possible to say that the TPM from the warm mix production were lower than from the hot mix production.

A more recent fuel consumption and gas/dust emissions measurement from an asphalt mix production (with 15% recycled asphalt used in the mixture) in a drum plant in Norway shows that the WAM Foam production resulted in a:

- 40% reduction in diesel consumption;
- 31% reduction in CO_2 emissions;
- 29% reduction in CO emissions and;
- 62% reduction in NO_x emissions,

compared to the hot mix (at identical production rates).

In the 2001 road experiment on FV82 in Norway mentioned previously, fuel consumption was measured and showed a 31.5% reduction. *[17]*

3.1.5 WAM Foam Summary

WAM Foam is a patented process that allows asphalt to be produced at temperatures between 100 and 120°C (212 and 248°F) and compacted at 80 to 110°C (176 to 230°F). A WAM Foam modified asphalt plant first mixes soft bitumen with the mineral aggregate in order to achieve pre-coating and then foamed bitumen, a hard bitumen grade, is introduced in a second step. With this procedure, good distribution of the bitumen is obtained and good workability during paving. Dense graded mixes have mainly been used but open graded and gap graded mixes are equally applicable.

Asphalt plants need to be modified with a foaming device and a good air extraction system is needed to compensate for the pressure build-up in the mixer while foaming. The equipment modifications for this process are therefore relatively extensive compared to the methods described in the next two sections. In a batch asphalt mixing plant the foamed bitumen is produced by injecting water into the bitumen pipe in a special nozzle system, just before the bitumen enters the mixer and an airgun is used to blow the foaming chamber and pipes clean after each foam injection. The production capacity of the plant can be maintained for all types of mixtures.

Laboratory studies and field trials that have been conducted and reported by the developers seem to show very similar results for WAM Foam productions and regular HMA production for typically monitored properties such as percent air voids, rut depths, smoothness, surface texture, skid resistance, stiffness modulus and fatigue. The first field trial was carried out in May 1999 in Norway, where many of the following trials have been conducted. Therefore, the performances of the pavements, some of which have been placed in cold weather, have been monitored for a few years.

Energy consumption measurements indicate a 30 to 40% reduction and emissions measurements indicate a 30 to 90% reduction, the most reductions being for NO_x, BSM (Benzene Soluble Matter) and PAC (Polycyclic Aromatic Compounds) emissions.

3.2 ASPHA-MIN ZEOLITE

Aspha-min zeolite is a product of Eurovia GmbH, Germany. It is a manufactured natrium-aluminum silicate which has been hydro-thermally crystallized. It contains approximately 21% water by weight and is released in the temperature range of 85-180°C (185-360°F). Eurovia recommends adding Aspha-min to an asphalt mixture at a rate of 0.3% by mass of the mix, which enables approximately a 30°C (54°F) reduction in production and placement temperatures. *[20]*

When Aspha-min is added to the mix at the same time as the binder, water is released which creates a volume expansion of the binder that results in an asphalt foam and allows increased workability and aggregate coating at lower temperatures. *[8]*

Eurovia states that all known bitumen, polymer modified bitumen and recycled asphalt (RAP) can be used in this process. Also, all normal mineral aggregates and fillers can be used and therefore no modifications to a normal mix design are needed. The addition into the mixing process is done through special devices with a similar procedure as adding certain types of fibers and does not prolong the mixing process. *[7]*

3.2.1 The Asphalt Plant

The zeolite can be added directly into the pugmill in a batch plant, through the RAP collar, or pneumatically fed into a drum plant using a specially built feeder. The developers of Aspha-min more specifically describe that specially designed feeders are not necessary, the zeolite can be added to the filler by hand or if the plant is equipped with a feeder for fibers, it can be used. But specially designed feeders are available for both drum and batch plants. *[21]*

In the NCAT road trial described in next section, a drum plant was used. A vane feeder controlled the addition rate and then the zeolite was pneumatically blown into the drum, at the same point as the asphalt cement, using an existing fiber addition line. *[8]*

Figure 3.1: Feeder (right) and an existing fiber addition line for Aspha-Min zeolite. *[8]*

3.2.2 Laboratory Studies

A laboratory study was conducted by the National Center for Asphalt Technology (NCAT) in the USA to determine the applicability of Aspha-min zeolite to typical paving operations and environmental conditions commonly found in the US. Two aggregate types, granite and limestone, and two binder grades, PG 64-22 and PG 58-28, were used. The Superpave gyratory compactor was used for the mix preparation but a vibratory compactor was used to determine the mixes' compaction ability over a range of temperatures. Mixes were therefore compacted using a vibratory compactor at 149°C, 129°C, 110°C and 88°C (300°F, 265°F, 230°F and 190°F) with the mixing temperature approximately 19°C (35°F) above the compaction temperature. The main results from the study are: *[8]*

- The addition of Aspha-min lowers the measured air voids in the gyratory compactor. The warm mix using PG 64-22 binder had almost the same air void level as the control mix using the PG 58-28 binder. This suggests that the zeolite additive lowered the mixing and compaction temperature by one asphalt grade;
- the addition of zeolite improves compaction in the vibratory compactor over the control mixture for all binder (although more pronounced for the stiffer binder, PG 64-22), aggregate and temperature combinations. The zeolite reduced the air void content by 0.65% on the average and improved compaction at temperatures as low as 88°C (190°F);
- the addition of zeolite did not affect the resilient modulus, i.e. the zeolite did not increase or decrease the stiffness of the mixtures for any compaction temperature. But the resilient modulus decreased as the compaction temperatures decreased and air voids increased;
- the addition of zeolite did not affect the rutting potential of a mixture. The rut depths increased as the temperatures decreased for all factor combinations;
- there was no change in strength at a particular age time for either the hot or the warm mixtures which means that there is no evidence to support the need for a cure time before traffic can be allowed on the asphalt mixture with zeolite;
- the lower mixing and compaction temperatures used when producing WMA with Aspha-min may increase the potential for moisture damage. The lower mixing temperatures can result in incomplete drying of the aggregate and the resulting water trapped in the coated aggregate may cause moisture damage;
- a Tensile Strength Ratio (TSR) test was used to determine the moisture sensitivity of the mixes. The addition of zeolite lowered the TSR value as compared to the control mixture but still resulted in an acceptable value, but visual stripping was

observed in both mixes produced at 121°C (250°F). To determine if the moisture resistance of the zeolite mix could be increased, anti-stripping agents were evaluated. A two-stage addition of 1.5% hydrated lime resulted in acceptable performance in terms of cohesion and moisture resistance and it decreased the rutting rate.

The NCAT report concludes by giving a few recommendations for using Aspha-min zeolite:

- The optimum asphalt content should be determined without the addition of Aspha-min;
- if mixing temperature is < 135°C (275°F), then either the high temperature grade can be bumped by one grade, or hydrated lime can be added to counteract the tendency for increased rutting with decreasing production temperatures;
- if tensile strength ratio test results are not favorable, hydrated lime should be added to the mix as an anti-stripping agent to increase the tensile strength ratio.

3.2.3 Field Trials

In conjunction with the NCAT laboratory study a field demonstration project was constructed in Florida in February 2004, where a parking lot was paved. The control mix was a fine graded Superpave mix with 20% reclaimed asphalt pavement (RAP). The warm mix was produced by adding Aspha-min zeolite to the control mixture at a rate of 0.3% by weight of total mix. The zeolite was introduced into the plant using a specially built feeder as described earlier. Laboratory tests corresponded with the trends seen in the laboratory study. During paving, the crew observed that the warm mix was more workable than the control mix. Equal densities were obtained in the warm and control sections. An assessment one year after placement showed no signs of distress and that the zeolite mixture was equally resistant to moisture damage as the control mix. It should be noted though that the sections do not receive regular traffic. *[8]*

A number of Aspha-min test sections and regular HMA comparison sections have been constructed by Eurovia GmbH. Three years after placement of the first ones, Eurovia reported that no significant changes were observed in surface characteristics and the zeolite sections were comparable to the traditional hot mix asphalt comparison sections. *[7]*

3.2.4 Environmental Benefits

Measurements conducted and reported by Eurovia GmbH showed a 30% reduction in energy consumption because of a 30-35°C (86-95°F) reduction in mix temperature. Measurements also indicated a 75% reduction in fume emissions resulting from a 26°C (47°F) reduction in production temperature. Measurements at the application site indicate over 90% reduction in fume emissions when the mix temperature was reduced from 175°C (347°F) to 140°C (285°F) and in all cases when zeolite has been added and temperatures been reduced, odor has significantly reduced and crew members have confirmed improved working conditions. *[7]*

3.2.5 Aspha-min Zeolite Summary

Aspha-min zeolite is a crystalline hydrated aluminum silicate and contains approximately 21% water by weight. It is recommended to be added to an asphalt mixture at a rate of 0.3% by mass of the mix, which enables approximately a 30°C (54°F) reduction in production and laying temperatures. When it is added to the mix at the same time as the binder, water is released which creates a volume expansion of the binder that results in an asphalt foam and allows increased workability and aggregate coating at lower temperatures.

The addition into the mixing process is done through special devices with a similar procedure as adding certain types of fibers and does not prolong the mixing process. Therefore, if a plant is equipped with a feeder to add fibers to a mix, it can be used but if specially designed feeders are preferred they are available. Either way, equipment modifications are at least not as extensive as for the WAM Foam method.

The laboratory studies and field trials discussed seem to give very similar results for the mixtures with zeolite and the regular hot mixtures. Exceptions were that the zeolite additive lowered the measured air voids in the gyratory compactor and improved compaction over the control mixture but lowered the tensile strength ratio value although resulting in an acceptable value. An anti-stripping agent may be desirable to counteract moisture damage and rutting potential with decreasing temperatures.

During paving, crew members have observed that the Aspha-min zeolite warm mix is more workable than the control mix and that odors are significantly reduced. Energy consumption measurements indicate a 30% reduction and emissions measurements indicate a 75% to 90% reduction.

3.3 Sasobit Wax

Sasobit wax is a product of Sasol Wax International and has been marketed in Europe and Asia since 1997. Sasobit is a mixture of long chain hydrocarbons produced from coal gasification using the Fischer-Tropsch synthesis and is also known as a FT paraffin wax. Sasol Wax states that it does not contain ash-forming materials (metals) and contains no hetero-atoms such as chlorine, sulphur, nitrogen and oxygen. Therefore, it is stated that it has good oxidation and ageing stability and may be stored indefinitely.

Sasobit's melting point is at about 100°C (212°F) and it is completely soluble in bitumen at temperatures above 120°C (248°F), and it does not separate out on storage. It reduces viscosity at working temperatures which makes the asphalt easier to process, provides the option of reducing working and mixing temperatures and thereby reducing fume emissions, saving energy and reducing production cycle times. Sasol Wax states that Sasobit makes it possible to upgrade softer grades of asphalt to harder grades while at the same time working to overcome deformation and bleeding at high performance temperatures. According to Sasol Wax the optimum addition of Sasobit has been found to be 3% by weight of the bitumen. *[22]*

Sasobit's ability to lower the viscosity of the asphalt binder, during both the asphalt mixing process and placement, allows working temperatures to be decreased by 18-54°C (32-97°F). Below its melting point it forms a crystalline network structure that may add stability. *[9]*

Sasobit can be combined with polymers which contribute to elasticity at low temperatures. This ability led to the development of Sasoflex which is a compound of

Sasobit, polymer and a cross-linking agent (Sasolink). The Sasobit component (a plastomer) improves high temperature stiffness, while the polymer component (an elastomer) maintains the flexibility at lower temperatures. *[22]*

3.3.1 The Asphalt Plant

Sasobit is available as flakes for molten additions or small pellets for direct addition to the mix (see Figure 3.2). In Europe, South Africa and Asia, the wax has been added directly to the aggregate mix as pellets or as molten liquid via a dosing meter. There has been no indication of a difference in stability or flow for mixes produced in this manner as compared to premixing with the binder. In the US, Sasobit has been blended with the binder at the terminal and blown directly into the mixing chamber at the same point as fibers are added to stone matrix asphalt (SMA) mix. *[9]*

Information from Sasol Wax states that Sasobit can be blended into hot bitumen at the asphalt plant using a simple stirrer, a high shear mixer is not required. *[23]*

Figure 3.2: Sasobit wax pellets. *[24]*

3.3.2 Laboratory Studies

A laboratory study was conducted by NCAT to determine the applicability of Sasobit in the US. Two aggregate types, coarse graded granite and limestone, and two binder grades, PG 64-22 and PG 58-28 were used. Three different versions of Sasobit modified binders were developed from these two binder grades as described in Table 3.3.

Table 3.3: The three different versions of Sasobit modified binders that were developed from the two binder grades, PG 64-22 and PG 58-28, by adding either 2.5% Sasobit or 4% Sasoflex.

Original binder grade	Addition	Resulting Sasobit modified binder
PG 58-28	2.5% Sasobit	PG 64-22
PG 58-28	4% Sasoflex	PG 70-22
PG 64-22	4% Sasoflex	PG 76-22

The Superpave gyratory compactor was used for the mix preparation but a vibratory compactor was used to determine the mixes' compaction ability over a range of temperatures. Mixes were therefore compacted in a vibratory compactor at 149°C, 129°C, 110°C and 88°C (300°F, 265°F, 230°F and 190°F) and the mixing temperature was approximately 19°C (35°F) above the compaction temperature. The main results from the study are: *[9]*

- The addition of Sasobit lowers the measured air voids in the gyratory compactor;
- a rolling thin-film oven (RTFO) test indicated reduced aging of the binder with the addition of Sasobit;
- the compaction temperature for the Sasobit modified PG 64-22 was 18°C (32°F) lower than for the PG 64-22 control, while producing approximately the same viscosity at in-service temperatures;
- the addition of Sasobit improved compaction in the vibratory compactor over the control mixture for all binder, aggregate and temperature combinations except for four cases, which were Sasoflex mixes at various temperatures. Those four cases are believed to be because of the elastomer part of the Sasoflex, which may have stiffened the binder enough to increase air void levels. Sasobit reduced air voids by an average of 0.87% for the PG 64-22 binder but less for the other binders

(0.11% and 0.07%) and improved compaction at temperatures as low as 88°C (190°F);

- the addition of Sasobit did not affect the resilient modulus but it did decrease as the temperatures decreased;
- rutting potential, found by the Asphalt Pavement Analyser (APA), generally increased with decreasing working temperatures but the use of Sasobit and/or Sasoflex significantly decreased the rutting potential, particularly at the lower temperatures. Therefore, the mixes containing Sasobit were less sensitive, in terms of rutting, to the decreased production temperatures than the control mixes were;
- results of the study support field data from Europe which indicate that there is not a need for a cure time before traffic can be allowed on the asphalt mixture with Sasobit;
- a Tensile Strength Ratio (TSR) test was used to determine the moisture sensitivity of the mixes. The addition of Sasobit both increased and decreased the moisture susceptibility compared to the corresponding control mixture. Reduced tensile strength and visual stripping were observed in both the control and Sasobit mixes produced at 121°C (250°F). Addition of a liquid anti-stripping agent improved the TSR values to acceptable levels;
- the lower mixing and compaction temperatures used when producing warm asphalt with any such warm mix additive, can result in incomplete drying of the aggregate and the resulting water trapped in the coated aggregate may cause moisture damage;
- to validate the TSR results, the Hamburg wheel-tracking device, which predicts moisture damage, was used. Results indicated good performance in terms of moisture susceptibility and rutting for the mixes containing Sasobit and anti-stripping agent as well as mixes containing Sasoflex. The addition of anti-stripping agent along with Sasobit produced the lowest rutting rate.

The NCAT report concludes by giving a few recommendations for using Sasobit wax:

- The modified binder including Sasobit or Sasoflex needs to be engineered to meet the desired Performance Grade;
- based on the compaction and rutting results, a minimum mixing temperature of 129°C (265°F) and a minimum compaction temperature of 110°C (230°F) is recommended;
- if mixing temperature is < 129°C (265°F), the high temperature binder grade should be bumped by one grade to counteract the tendency for increased rutting with decreasing production temperatures;
- if moisture sensitivity test results are not favorable, an anti-stripping agent should be added to the mix to increase the resistance to moisture.

The low temperature behavior of Sasobit modified asphalts was tested by Sasol Wax with a series of cooling tests simulating service conditions. The method is not described more precisely than that rigidly mounted asphalt test samples were subjected to cooling at the rate of 10°C/hr and the tensions created by thermal shrinkage and the break temperatures were measured. The results were:

Table 3.4: The low temperature behavior of Sasobit modified asphalts, found by measuring the tensions created by thermal shrinkage and the break temperatures. *[23]*

	Max thermally induced tension [N/mm^2]	Break temperature [°C (°F)]
SMA 0/11 S; B 50/70	4.4	-25.5 (77.9)
SMA 0/11 S; B 50/70 + 3% Sasobit	4.5	-24.5 (76.1)
Gussasphalt 0/11; B 30/45	6.0	-26.5 (79.7)
Gussasphalt 0/11; B 30/45 + 3% Sasobit	5.9	-25.5 (77.9)
Gussasphalt 0/11; PmB 45	6.8	-30.0 (86.0)
Gussasphalt 0/11; PmB 45 + 3% Sasobit	7.0	-30.0 (86.0)

3.3.3 Field Trials

In 2005, the Maryland State Highway Administration published two reports; Performance Evaluation of High RAP (reclaimed asphalt pavement) Base Mixture Containing Sasobit and Performance Evaluation of High RAP Surface Mixture Containing Sasobit. The purpose of the evaluations was to examine the effects of Sasobit on asphalt mixture performance when used as a compaction aid in mixtures incorporating high percentages of RAP. These evaluations did therefore not use a different production temperature for the Sasobit mixes than for the control mixes. In the first report, two 19 mm base course mixtures were evaluated, control and Sasobit. They incorporated 45% RAP and were produced in a drum plant. The Sasobit was blown into the mixture at a rate of 1.5% by weight of total asphalt (which, notably, is below the 3% recommended rate), using the fiber additive system at the plant.

The following results are from laboratory testing that was conducted on plant produced samples that were compacted to a target air void content of 7% using a gyratory compactor:

- Sasobit marginally increased the high temperature stiffness of the mixture, as indicated by the dynamic modulus master curve (AASHTO TP62-03);
- aging (as measured by changes in mixture stiffness due to long-term oven conditioning (AASHTO R30-02 and AASHTO TP62-03)), rutting (as measured by repeated load permanent deformation tests), fatigue cracking (as measured by uniaxial tension-compression fatigue tests) and thermal cracking resistance (as evaluated using a simplified thermo-visco-elastic analysis (AASHTO T322)) were not significantly affected by the addition of Sasobit;
- Sasobit appeared to slightly improve the resistance of mixtures to moisture damage, as measured by tensile strength ratio;
- the critical cracking temperature for both mixtures was -24°C (-11°F).

The main conclusion drawn from the evaluation was that the use of Sasobit as a compaction aid had only minor effect on the mechanical properties of the mixtures and that there is no adverse effect on pavement performance from the use of Sasobit as a compaction aid in high RAP content mixtures. *[25]*

In the second report, Performance Evaluation of High RAP Surface Mixture Containing Sasobit, two 9.5 mm surface course mixtures were evaluated, control and Sasobit. They incorporated 35% RAP and like before, were produced in a drum plant and the Sasobit was blown into the mixture at a rate of 1.5% by weight of total asphalt, using the fiber additive system at the plant.

The findings from the surface course report are very similar to the base course report. The main difference was that the increase in high temperature stiffness was slightly less than in the base course report and the critical cracking temperatures were -30°C (-22°F) for the control mix and -28°C (-18°F) for the Sasobit mix, i.e. not a significant difference but slightly lower than in the base course report. *[26]*

Experience during the production and placement showed that the Sasobit mixture was much easier to handle and all compaction targets were made with rolling cycles reduced by 40% as compared to the control mixture. *[27]*

Following are a few pictures from the Maryland State Highway Administration, taken during the production and placement for the performance evaluation.

Figure 3.3: Pellet packets and distribution box (blue box in the center). *[24]*

Figure 3.4: Plant retrofitted for Sasobit wax addition. *[24]*

Figure 3.5: Distribution box with part of augers showing. *[24]*

Figure 3.6: Sasobit flowing from distribution box to feeder tube. *[24]*

Figure 3.7: Surface course mix with Sasobit wax and 35% RAP. *[24]*

Figure 3.8: Surface course mix with 35% RAP, without Sasobit wax. *[24]*

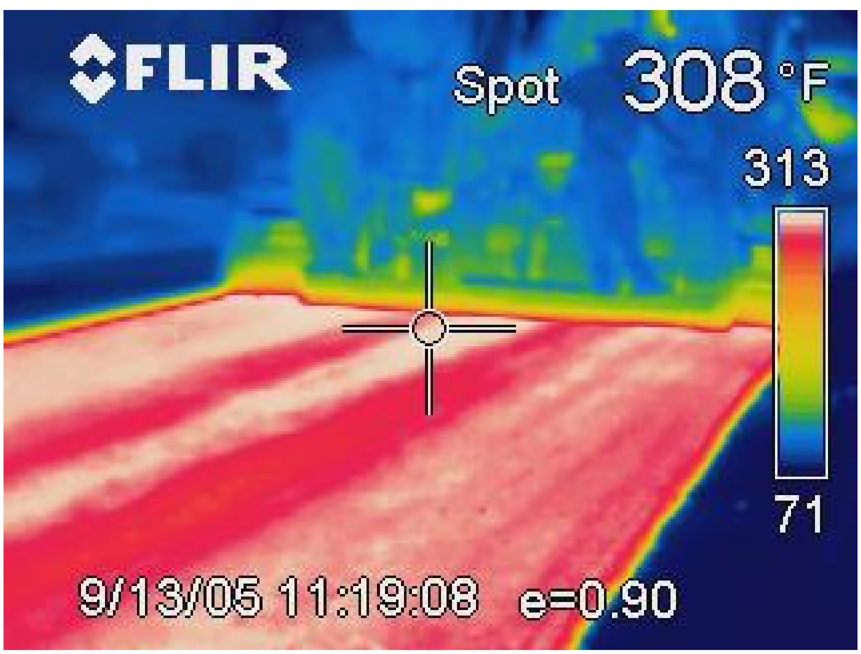

Figure 3.9: Thermal picture of mat without Sasobit. Temperature appears to be fairly consistent across the mat. *[24]*

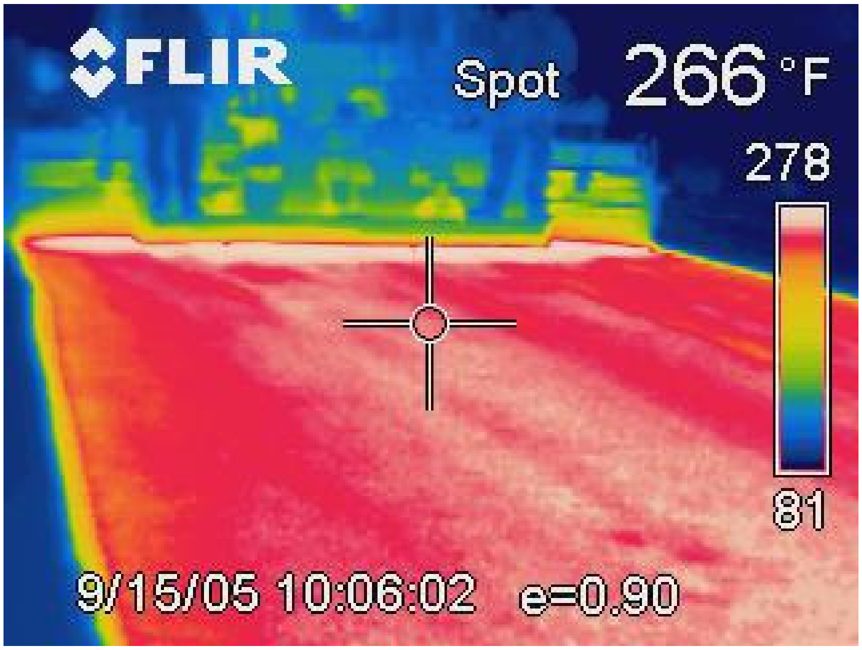

Figure 3.10: Thermal picture of mat with Sasobit. A lower compaction temperature was used here than in Figure 3.9 and still the temperature appears to be fairly consistent across the mat. *[24]*

On its webpage, Sasol Wax counts 143 road projects and trials that have been constructed. Most of them are in Germany, but also in Czech Republic, Denmark, France, Hungary, Italy, Malaysia, Netherlands, New Zealand, Norway, UK, South Africa, Sweden and Switzerland. The aggregate types used were various dense graded mixes, stone matrix asphalt (SMA) and gussasphalt and Sasobit addition rates were most often 3% but ranged from 1% to 4.5%. *[28]*

3.3.4 Environmental Benefits

Sasol Wax states that a 20°C (68°F) reduction in production temperature results in a 20% reduction in energy consumption. *[29]* No information was found about emissions measurements.

3.3.5 Sasobit Wax Summary

Sasobit wax is a FT paraffin wax, a mixture of long chain hydrocarbons produced from coal gasification. Sasobit's ability to lower the viscosity of the asphalt binder at working temperatures makes the asphalt easier to process and provides the option of reducing working and mixing temperatures (by 18-54°C (32-97°F)) and thereby reducing fume emissions, saving energy and reducing production cycle times. Sasol Wax states that the optimum addition of Sasobit has been found to be 3% by weight of the bitumen. Below its melting point (100°C (212°F)) it forms a crystalline network structure that leads to added stability.

The wax can be added directly to the aggregate mix or premixed with the binder and it can be blended with the binder at the terminal and blown directly into the mixing chamber at the same point as fibers were being added to SMA. This indicates that the equipment needs are similar as for the Aspha-min zeolite addition, i.e. not great, at least not as extensive as for the WAM Foam method.

The laboratory and field studies discussed seem to show more prominent differences between the control mix and the warm mix than those for WAM Foam and Aspha-min zeolite. Sasobit wax; lowered the measured air voids, reduced aging of the binder, lowered compaction temperature, improved compaction, lowered sensitivity in terms of rutting for the decreased production temperatures, indicated good performance in terms of moisture susceptibility and rutting and marginally increased high temperature stiffness. Sasobit as a compaction aid in high RAP content mixtures had no adverse effect on pavement performance.

3.4 Other Warm Mix Asphalt Methods

3.4.1 Asphaltan B Wax

Asphaltan B is a product of Romonta GmbH, Germany. It is a low molecular weight esterified wax and enables the application of asphalt blends at lower temperatures by reducing viscosity. Romonta recommends using 2 to 4% of weight relative to the binder. *[30]* It can be added to the asphalt mixing plant or directly at the binder producer and it can also be added to polymer modified binders. Similar to Sasobit, it acts as an asphalt flow improver by increasing compactability and resistance to rutting. The melting point of Asphaltan B is approximately 99°C (210°F) and it allows reduced production temperatures but Romonta does not specify how much the production temperature can be lowered. *[14]*

3.4.2 Evotherm

Evotherm is a non-proprietary technology based on a chemical process that includes additives to improve coating and workability, adhesion promoters and emulsion agents. The Evotherm product is delivered in the form of an emulsion with a relatively high asphalt residue (approximately 70%). Unlike traditional asphalt binders, Evotherm is stored at 80°C (176°F). The water in the emulsion is released from the Evotherm as steam when it is mixed with the hot aggregate. The resulting warm mix appears like a hot mix in terms of coating and color.

The first Evotherm project was constructed in South Africa in 2003. In July 2005, the first trial in the US was constructed where 660 tons were laid on a county road near Indianapolis, Indiana. It was produced in a hybrid batch/drum plant in drum plant mode, using a chemistry package from MeadWestvaco. The Evotherm was added to a 12.5 mm nominal maximum aggregate size coarse-graded Superpave mix produced with crushed dolomite and 15% RAP. Discharge temperatures from the drum were about 93°C (200°F) and the aggregate was completely coated at that temperature. The mix was laid at an average depth of 50mm (2 in) and temperatures behind the screed were between 71 and 93°C (160 and 200°F). There were no visible emissions around the paver and the mix did not show any signs of tenderness. *[31]* NCAT representatives tested material from this field trial and their results were: *[15]*

- Evotherm improved the compactability of the mixtures in the vibratory compactor. Statistics indicated an average reduction in air voids up to 1.5%;
- addition of Evotherm does not affect the resilient modulus of an asphalt mix compared to mixtures with the same PG binder;
- addition of Evotherm generally decreased the rutting potential of the mixes;
- lower temperatures used in producing WMA may increase the potential for moisture damage.

Another Evotherm trial was conducted in Ontario, Canada, and reported by J.K. Davidson in August 2005. The trial was placed on a mainline truck exit and a parking area. The mix was produced in a batch plant at 130°C (266°F). The results were: *[32]*

- The Evotherm mix did not cause any problems in the mixing process or with handling the emulsion. The emulsion was slightly slower to pump up to the asphalt cement weigh hopper;
- because the Evotherm emulsion is only about 70% residue, the quantity of emulsion needed per ton of mix is 45% higher. Therefore the batch size had to be reduced because of the capacity of the asphalt cement weigh hopper;
- the Evotherm mixes used 2.3 m^3 of gas per ton of mix produced while the hot mixes usually use about 10 m^3;
- during paving there were no indications of tearing behind the screed or of the mix agglomerating;
- the breakdown roller traveled right up to the back of the paver without evidence of pushing or shoving of the pavement mat.

3.4.3 Summary of Other Methods

Asphaltan B wax seems to be similar to Sasobit wax but information about it are not as easily accessible and it seems that not as much research has been done with it.

Of all the methods that are discussed in this paper, the Evotherm method is the only method that is non-proprietary. It is also based on a slightly different idea than any of the other mixes since it is based on a chemical package that includes various agents and the product is delivered in the form of an emulsion. Information about these methods is not as easily accessible as they are for the WAM Foam, Aspha-min zeolite and Sasobit wax methods.

3.5 Warm Mix Asphalt's Advantages and Disadvantages

As can be seen from chapters 3.1 through 3.4, the amount of testing that has been done for the methods varies; some have been tested extensively and even put in commercial use but others have not been reportedly tested as much. From the main research done so far and their findings, it seems safe to say that the quality of WMA is comparable to hot mix asphalt in most ways. However, it is only about 3 to 8 years (depending on method) since the earliest WMA field tests were started and therefore its long-term performance is still unproven. A pavement life can be 15 to 20 years or more and therefore there is still quite some time before WMA's affect on the pavement's service life will be fully known.

3.5.1 Emissions

From the measurements that have been conducted and reported, it is clear that fume emissions during WMA production are significantly lower than during hot mix asphalt production. TPM, BSM and PAC measurements for a WAM Foam production were in the range 2-10% of that for a HMA production. Other emissions measurements were between 20 and 70% of that for HMA.

For paving projects that are not in open air, for example in tunnels, workers exposure to emissions is multiplied and therefore the reduced emissions of WMA could be especially desirable for such situations as well. Studies reported in the NIOSH review indicate significant changes in pulmonary function in 1 of 44 workers engaged in open-air asphalt paving but in 3 of 9 workers engaged in underground asphalt paving. *[11]*

The importance of this WMA property will greatly depend on environmental awareness and regulations in each country and at each location within a country. Where emission regulations are getting stricter, which is the case for most countries participating in the Kyoto Protocol for example, the reduced emissions can become a very important benefit. Within each country, the reduced emissions are likely to especially encourage WMA usage in densely populated areas where day to day air quality is most important, and according to the considerations above, perhaps also in non-open air situations. However, unless there are requirements from authorities or special incentives for asphalt producers to lower emissions, there is not a direct benefit for the asphalt producer. If there is not an economical benefit for the producer, the realistic importance of this WMA benefit in practice is limited.

3.5.2 Energy Consumption

The reduced energy consumption is another benefit of WMA that is greatly emphasized in literature. Where the energy consumption for a WMA production was measured, it was 60-80% of that for HMA production, depending on how much the production temperature was lowered. The importance of this benefit depends on what sort of energy is used for the production process and how polluting and expensive it is. In most countries the energy cost is relatively high and therefore this benefit can be very important for the asphalt producer. Where sustainable and/or relatively inexpensive energy sources are used for asphalt production, this benefit is less important. It also needs to be taken into count that there is additional cost involved in using WMA, i.e. equipment modifications and patent fees for the WAM Foam method and cost of additives for the Aspha-min zeolite and Sasobit wax methods. Cost estimates are detailed in chapter 4.2.3.

3.5.3 Mixture Viscosity

Other possible benefits that have not been as prominent in literature as the reduced emissions and energy consumption are various benefits related to the lower viscosity of the warm mixtures. Generally, improved workability can have various effects throughout the production and placement process. For example, the improved workability has the potential of allowing the following benefits.

1. Lower working temperatures, leading to:
   - Energy savings during production;
   - reduced emissions;
   - decreased cooling rate due to smaller difference between ambient and compaction temperatures.
2. Increased temperature gap between mixing and compaction (by using regular HMA mixing temperatures), allowing:
   - Increased haul distances;
   - increased time available for compaction, thereby for example extended paving season into the colder months of the year.

3. Easier compaction (by using regular HMA mixing temperatures), which are beneficial:
   - During extreme weather conditions;
   - for stiff mixes and mixes with RAP;
   - for reducing amount of necessary roller compaction.
4. A combination of items 1 and 2 or items 1 and 3, by reducing production temperatures by some amount and increasing the temperature gap or facilitating compaction by some amount.

The effect the three warm mix methods have on viscosity and the information available varies somewhat and this is therefore discussed more thoroughly for each method.

As mentioned previously, the normal compaction temperatures for WAM Foam are between 80 and 110°C (176 and 230°F), depending on the stiffness of the binder. *[16]* Exact information about the viscosity at compaction temperatures for the WAM Foam process was not found. Considering that normal mixing temperatures have been 100 to 130°C (212 to 266°F) this gives a haul "window" of about 20°C (54°F) on average, which is similar to a regular HMA production. Percent air voids measurements for WAM Foam tests have showed either comparable results to regular HMA production or sometimes slightly higher voids contents. The reduction in air voids that test results for Aspha-min zeolite and Sasobit wax have showed is therefore not as clear for WAM Foam. Based on the information given, production, compaction and cessation temperatures and time available for compaction can seemingly be controlled slightly by choosing appropriate stiffness of the binder.

According to information from Kolo Veidekke, WAM Foam mixes that have been produced at "higher" temperatures have also been placed at "higher" temperatures, so they do not have information about the mix's performance if used to increase the temperature gap rather than lower the working temperatures. *[18]* The conclusion drawn from the available information is therefore that apart from reducing working temperatures, the reduced viscosity from using the WAM Foam process can to some extent be used as a compaction aid for example during extreme weather conditions or for RAP. But based on available air voids measurements for example, it can not be stated that the amount of roller compaction can be reduced. The viscosity reduction might also possibly be used to increase the temperature gap although this possibility needs to be examined. And of course, some combination of the above should also be possible.

The Aspha-min zeolite lowers percent air voids compared to a regular hot mixture produced and compacted at same temperatures. The NCAT study showed that the zeolite lowered the mixing and compaction temperatures by one asphalt grade. The NCAT densification results show that for the same compactive effort, percent air voids are reduced when the zeolite is used. This implies that the zeolite addition reduces the viscosity of the binder. According to information from Eurovia, the mix is compactable until it cools down to approximately 100°C (212°F). *[7]* This indicates that the zeolite does not lower the cessation temperature of the mix compared to a regular hot mix. Therefore, the conclusion drawn is that as long as compaction temperatures are above the cessation temperature there is reduced viscosity. It can be used to decrease the mixing temperature, increase the temperature gap or to ease compaction or a combination of these, as described at the beginning of this section.

As was described in chapter 3.3, the NCAT study showed that Sasobit reduces aging of the binder and generally improves compaction. It can reduce viscosity in the mixing and compaction temperature range while producing approximately the same viscosity at in-service temperatures. Figure 3.11 shows that the compaction temperature for the Sasobit modified PG 64-22 is approximately 18°C (32°F) lower than the compaction temperature for the PG 64-22 control. At about 105°C (221°F) the difference in viscosity starts to decrease. The congealing temperature of the Sasobit wax is approximately 100°C (212°F) so at about this temperature the wax starts to congeal. At about 82°C (180°F) the viscosities of the Sasobit mixture and the control mixture are similar. The NCAT study also showed that Sasobit improved compaction at temperatures as low as 88°C (190°F). *[9]* For a dense graded HMA mix the cessation temperature is about 79°C (175°F). *[12]*

This information indicates that Sasobit lowers the compaction temperature (reduces the viscosity) until the mix has cooled to about 80 to 85°C (176 to 185°F) and therefore does not lower the cessation temperature of the mix. From its congealing temperature and until the mix has cooled to 80-85°C (176 to 185°F), the wax's ability to reduce the viscosity compared to regular HMA gradually decreases. Therefore, as long as compaction temperatures are above about 85°C (185°F) there is definitely reduced viscosity from the addition of the wax.

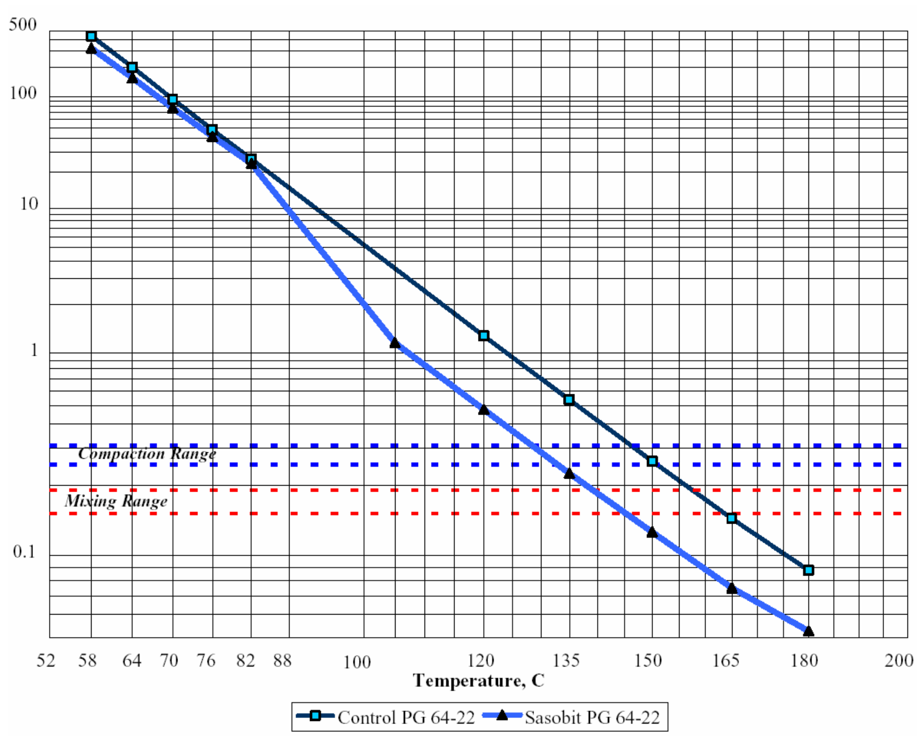

Figure 3.11: Viscosity [Pa-s] as a function of temperature [°C] from the NCAT study for a Sasobit wax mixture and a corresponding control mixture. *[9]*

The viscosity reduction from the Sasobit can be used in all of the ways listed at the beginning of this section, i.e. to reduce mixing temperatures, increase the temperature gap or ease compaction or a combination of these. As an example, experience during production and placement in the Sasobit evaluation in Maryland showed that the Sasobit mixture was much easier to handle and all compaction targets were made with rolling cycles reduced by 40% as compared to the control mixture. *[27]* Also, when it comes to applications in cold environmental temperatures the producers of Sasobit prefer to use the term "viscosity reduced asphalt" rather than "warm mix asphalt". According to information from Sasol Wax, many building companies in Scandinavia are adding 3% Sasobit to the bitumen in order to stabilize the very soft bitumen grades in summer. They also state that the Sasobit modification gives a side benefit for paving in cold temperatures. Depending on the addition level, the time available for truck transport of the asphalt mix can be significantly increased and can therefore allow longer haul distances. In the same sense it can increase good compaction behavior in cold and windy conditions that normally would cool down regular HMA too quickly. *[33]*

A possible side benefit of WMA is a shorter construction time because traffic should be able to be allowed on the pavement sooner than for regular hot mix asphalt. The warm mixture is not as hot when compaction starts so less time is required for it to cool down to temperatures for traffic or for the next lift to be placed if that is the case. See Figure 3.11; the Sasobit wax reduces viscosity until cessation temperature is reached which means that compaction down towards the cessation temperature is easier but after that the wax increases the pavement's stability. According to the NCAT report, field data from Europe confirm this. Results from the NCAT report on Aspha-min zeolite also indicate this since there was no change in strength gain at a particular age time for either the hot or the warm mixtures which means that there is no evidence to support the need for a cure time before traffic can be allowed on the asphalt mixture with zeolite.

3.5.4 Laboratory Performance

The key performance parameters of asphalt that laboratory performance tests try to characterize and mix designs strive to achieve are primarily: *[34]*

- **Deformation resistance** (stability) – the asphalt pavement should not deform (rut or shove) under traffic loading;
- **fatigue life** – a measure of one of the principal modes of pavement failure, fatigue cracking, which can result when it is subjected to repeated loads over time;
- **tensile strength** – a good indicator of cracking potential. The asphalt pavement should not crack when subjected to low ambient temperatures or repeated loads;

- **stiffness** – characterized by elastic or resilient modulus and can affect parameters like rutting or shoving;
- **moisture susceptibility** – the asphalt pavement should have adequate moisture damage resistance and not degrade substantially from moisture penetration;
- **durability** – the asphalt pavement should not suffer excessive aging during production and service life. Durability is related to air voids content and the asphalt binder film thickness around each aggregate particle. Excessive air voids increase the pavement's permeability and allow oxygen easier access to more asphalt binder thus accelerating oxidation and volatilization. If the film thickness surrounding the aggregate particles is insufficient, it is possible that the aggregate may become accessible to water through holes in the film. If the aggregate is hydrophilic, water will displace the asphalt film and the cohesion between the asphalt and the aggregate will be lost. This is called stripping.

3.5.4.1 Deformation

As mentioned above, the two NCAT studies show that both Aspha-Min zeolite and Sasobit wax allow reduced air void content for the same compactive effort by reducing the viscosity of the mix. Similar results are reported for the WAM Foam process, where same or slightly higher air void contents are achieved while compacting at lower than normal temperatures. Air voids content in a mix is very important and is closely related to stability and durability. Reduced air voids content, generally down to about 3-4%, can decrease rutting, raveling and moisture damage potential and increase stiffness and strength. *[12]*

Generally in both the wax and zeolite NCAT studies, rutting increased with decreasing temperatures. But Sasobit wax decreased the rutting potential compared to regular hot mix both with and without an anti-stripping agent but did not affect rutting according to the evaluation in Maryland. Results also indicate that Sasobit wax gives added stability to the mix. Aspha-Min zeolite had no effect on rutting potential and did not decrease rutting rate until an anti-stripping agent was added to the mix. Rutting was monitored for three years after placement for a WAM Foam mix and a regular hot mix and results were similar. Rutting resistance is a factor that needs careful attention in WMA design since it generally increases significantly with decreased production and compaction temperatures and the different warm mix methods perform differently. Therefore, according to available tests it seems that Sasobit and WAM Foam give satisfactory rutting resistance results but results for Aspha-min indicate that it does not negate the increased rutting susceptibility from the lower temperatures as well as the other two methods without the assistance of anti-stripping agents.

Surface texture, smoothness and skid resistance have all been tested and, the former two, monitored for three years after placement of a WAM Foam mix and a regular hot mix for comparison and all results are reported to have shown similar results. Similar measurements for the other two methods were not found. Apart from implying acceptable workability of the mix, these results do not directly report a warm mix characteristic since they mainly indicate that the aggregate characteristics of the mixture give good friction and that the right binder content was used.

Short-term aging of liquid binder occurs when it is mixed with hot aggregate. It is believed that short-term aging is reduced significantly because of the lower mixing temperatures for warm mix asphalt, possibly enhancing pavement durability. *[15]*

Sasobit wax reduced the aging of the binder according to the NCAT study but did not affect it according to the evaluation in Maryland. This indicates that Sasobit may increase the pavement's durability which further indicates that for a warm mixture with Sasobit the binder forms a sufficiently thick film around the aggregate particles during mixing and that air void contents are sufficiently low.

3.5.4.2 Fatigue Cracking

Fatigue cracking resistance for the WAM Foam process and the Sasobit wax process were similar to a regular hot mix and thermal cracking resistance was not affected by the addition of Sasobit wax. This indicates that these two methods do not stiffen the binder more than the control hot mixtures.

None of the three methods were found to affect the resilient modulus of a mixture, i.e. the stiffness, except for that the evaluation in Maryland found that Sasobit wax marginally increased the high temperature stiffness. But both of the NCAT reports found that the resilient modulus did decrease as the temperatures decreased.

3.5.4.3 Moisture Susceptibility

In the NCAT study the addition of Sasobit wax resulted in fluctuating moisture susceptibility results. The addition of zeolite lowered the tensile strength ratio value but still resulted in acceptable moisture susceptibility results. Reduced tensile strength and visual stripping were observed in both methods when produced at 121°C (250°F) and the reports conclude with saying that the lower production temperatures used when producing any such warm mixture may increase the potential for moisture damage. The lower temperatures can result in incomplete drying of the aggregates and the resulting trapped water in the coated aggregates may cause moisture damage. Both methods resulted in acceptable performance in terms of moisture susceptibility after anti-stripping agents were added and then rutting resistance was also increased. The evaluation in Maryland found that Sasobit wax slightly improved the resistance to moisture damage, but note that that study did not use lowered production temperatures. No reported research on the moisture susceptibility of WAM Foam was found but according to information from Kolo Veidekke they tend to get somewhat lesser values for WAM Foam in the lab, but that does not correlate to results from cores taken from the road. Visual inspections of the road do not indicate that this should be an issue.

3.5.5 Summary of Advantages and Disadvantages

The importance of the reduced emissions greatly depends on environmental awareness and regulations in each country and at each location within a country. Where emission regulations are getting stricter, the reduced emissions can become a very important benefit. Within each country, the reduced emissions are likely to especially encourage WMA usage in densely populated areas where day to day air quality is most important and in non-open air paving. However, unless there are requirements from authorities or special incentives for asphalt producers to lower emissions, there is not a direct benefit for the asphalt producer and if there is not an economical benefit for the producer, the realistic importance of this WMA benefit in practice is limited.

Where the energy consumption for a WMA production was measured, it was 60-80% of that for HMA production, depending on how much production temperature was lowered. The importance of this benefit depends on what sort of energy is used for the production process and how polluting and expensive it is. In most countries the energy cost is relatively high and therefore this benefit can be very important for the asphalt producer. It also needs to be taken into count that there is additional cost involved in using WMA, i.e. equipment modifications, patent fees or cost of additives.

Generally for all the WMA methods it appears that cessation temperatures stay relatively similar as for HMA but the viscosity of the mixture is decreased at lower temperatures, i.e. until the mix cools down to its cessation temperature. Therefore, the mix can be allowed to cool closer to its cessation temperature without compromising adequate compactability. The effect on the cessation temperature can be stated with more confidence about the Sasobit method than the others since the amount of available information about its affect on viscosity is much more thorough than for the other two methods.

The reduced viscosity of the WMA methods has some other possible advantages than to lower production temperatures, especially if regular HMA production temperatures are used, but then the benefits of reduced energy consumption and emissions are sacrificed. These are benefits related to increasing the temperature gap between mixing and compaction and using WMA as a compaction aid for various conditions. These other application possibilities achieved by using regular HMA production temperatures have been most prominently marketed (and are therefore best understood) for Sasobit wax and least for WAM Foam, whose marketing has solely focused on the environmental benefits.

According to available tests it seems that Sasobit and WAM Foam give satisfactory rutting resistance results but results for Aspha-min indicate that it does not negate the increased rutting susceptibility from the lower temperatures as well as the other two methods without the assistance of anti-stripping agents. Research indicates that Sasobit wax reduces the aging of the binder which further indicates that Sasobit may increase the pavement's durability.

None of the three methods were found to affect the resilient modulus of a mixture, i.e. the stiffness.

Generally, the lower temperatures used for WMA can result in incomplete drying of the aggregates and the resulting trapped water in the coated aggregates may cause moisture damage. In the NCAT tests, both Aspha-min zeolite and Sasobit wax resulted in acceptable performance in terms of moisture susceptibility after anti-stripping agents were added and then rutting resistance was also increased. No reported research on the moisture susceptibility of WAM Foam was found but according to information from the developers, visual inspections of the road do not indicate that moisture susceptibility should be an issue.

These moisture susceptibility considerations are probably descriptive of possible difficulties that WMA producers may have to deal with. Finding the right balance between lowering the production temperatures, applying anti-stripping agents and achieving a sufficiently moisture resistant asphalt mixture might be a challenge when using WMA.

3.6 Cold Weather Paving

In order to evaluate WMA's suitability for cold weather conditions, a few general issues regarding cold weather paving are discussed in this section.

Compaction is especially important during cold weather paving. As ambient temperatures decrease, HMA cool down rates increase and the time available for compaction, before cessation temperature is reached, is reduced. Literature indicates that 20 Pa-s (200 poises) is a reasonable lower viscosity limit for compactability, i.e. cessation temperature. Dense, well compacted pavements have close aggregate-to-aggregate contact and will be more stable and have lower permeability. Achieving low permeability is especially important when compacting in cold weather.

The grade of asphalt cement in HMA influences compaction such that lower viscosity (soft) grades are mixed, placed and compacted at lower temperatures than harder grades. Soft grades are normally mixed at lower pugmill temperatures and have lower cessation temperatures. A mix made with softer grades than normally in order to improve compaction may be easier to compact at lower temperatures but it is likely to be unstable under summer traffic. Total compaction time between placement and cessation temperature for different grades is roughly the same. Asphalt modifiers such as hydrated lime, fibers, anti-oxidants, chemical anti-stripping agents, carbon black, rubber and polymers can each affect compaction in a different way. Cold weather compaction is not increased by the use of additives that increase viscosity. More viscous asphalt will probably have higher cessation temperatures.

The mix design process does not need to be altered for cold weather conditions but particular care must be taken to ensure that mixtures are not overly susceptible to moisture damage. Surface water infiltration can cause rapid deterioration under traffic when pavement surfaces compacted in cold weather are more permeable.

The relationship of base and mix temperature is important. With a cold base and low initial mat temperature, thin lifts cool rapidly. Compacting HMA pavements on a frozen base results in two problems; more rapid cooling will prevent adequate compaction and a wet thawed base can cause support failure. If the frozen base contains moisture the temperature drop is even greater. *[35]*

Of these issues discussed here, compactability and permeability, moisture susceptibility and binder grade, are of special interest regarding WMA for cold weather conditions.

Compactability is indeed well accounted for by the warm mix methods, since they all reduce the viscosity of the asphalt and have the capability of increasing compaction and thereby reducing permeability. Rutting measurements give an indication of in-service stability and, as discussed in chapter 3.5, Sasobit and WAM Foam appear to have adequate rutting resistance and Sasobit is said to increase in-service stability but Aspha-min does not affect rutting. All three methods should result in adequate stability but WAM Foam's and Sasobit's performances are more definite.

The discussion in chapter 3.5 revealed that achieving adequate moisture damage resistance may be a challenge when using warm mix methods. Since this is also a factor that needs special attention regarding cold weather conditions, it is very important for WMA in cold weather conditions. It seems clear that for cold weather paving with WMA, use of anti-stripping agents will be desirable, whether it will be necessary depends on other factors as well, for example aggregate quality and moisture content.

Considering the issues that have been discussed here above, WMA appears to be a viable option for cold weather paving. This can be said about all of the three methods, although there are slight differences in some of their measured properties. However, anti-stripping agents are likely needed to decrease rutting and moisture susceptibility. Many of the advantages gained when WMA is produced at regular hot mix asphalt temperatures are particularly beneficial for cold weather conditions. Of those listed at the beginning of section 3.5.3 are for example extended paving season and easier compaction during extreme weather conditions.

4. ICELAND

4.1 GENERAL INFORMATION

Average temperatures and monthly precipitations measured over the 30 year period from 1961 to 1990 for two locations in Iceland, Reykjavik and Akureyri, are shown in the following table. Reykjavik is located in the southwest part of Iceland and it is the largest urban area in the country and Akureyri, the largest town outside of the greater Reykjavik area, is in the northern part of the country.

Table 4.1: Average temperatures and monthly precipitations measured from 1961 to 1990 for Reykjavik and Akureyri. *[36]*

	Mean temperature in January [°C (°F)]	Mean temperature in July [°C (°F)]	Mean monthly precipitation for January [mm (in)]	Mean monthly precipitation for July [mm (in)]
Reykjavik	-0.5 (31.1)	10.6 (51.1)	75.6 (2.95)	51.8 (2.02)
Akureyri	-2.2 (28.0)	10.5 (50.9)	55.2 (2.15)	33.0 (1.29)

Two characteristics of the Icelandic climate are especially important for pavement design; a relatively small variation in temperature over the year and frequent temperature oscillations around 0°C (32°F) during the winter. *[37]*

In 2004, the length of Iceland's highway system, those roads that the Road Administration is responsible for, was about 13,000 km (8,080 mi) and about 4,500 km (2,800 mi) were paved, or about 35%. *[38]* In a report about the Road Administration's road construction plan for the year 2004 it says that a total of 623 km (387 mi) (3,737,000 m^2 (40,225,000 ft^2)) of pavement were replaced in the country, mainly surface dressing (BST) but HMA was only used for urban areas and roads with heavy traffic. *[39]* Generally, at places where HMA is available, it is used if traffic reaches 3000 AADT (Annual Average Daily Traffic, vehicles/day). *[40]* Of those 623 km (387 mi), 572 km (355 mi) was surface dressing and 51 km (30,500 tons) was HMA.

These numbers do not include most streets in urban areas. The City of Reykjavik is responsible for the largest part of urban area streets and the total length of the street system in Reykjavik is about 400 km (250 mi) and most of it is paved with HMA. *[41]* Exact numbers for the length of road systems in all other towns in the country are difficult to find but for the purpose of this paper the following rough estimation will do. Numbers from the statistical bureau of Iceland, Statistics Iceland, indicate that the population of Reykjavik as about 40% of all densely populated areas in the country. *[42]* Assuming approximately the same length of paved streets per person throughout the country, the total length of paved streets, other than those in Reykjavik and those that the Road Administration is responsible for, is about 600 km (370). These numbers are summarized in Table 4.2.

Table 4.2: Total length of the Icelandic road system and total length of paved roads operated by the Road Administration and the City of Reykjavik and an approximation of lengths for all other municipalities in the country.

	Road Administration	City of Reykjavik	Other municipalities	Total
Length of total road system [km (mi)]	13,000 (8,080)	400 (250)	600 (370)	14,000 (8,700)
Total length of paved roads (including surface dressing) [km (mi)]	4,500 (2,800)	400 (250)	600 (370)	5,500 (3,420)

4.2 WARM MIX ASPHALT IN ICELAND

4.2.1 Technical Issues

This section discusses the various technical issues related to paving in Iceland and how WMA fits into the country's paving environment, methods and standards.

4.2.1.1 Asphalt Usage in Iceland

Total hot mix asphalt production in Iceland is not known precisely from year to year, but a rough estimate is about 250,000 tons per year. Asphalt production, of course, varies between years but this is a reasonable estimate for an average year. *[43, 44]*

A report that examines the difference in feasibility between HMA and surface dressing in Iceland based on life-cycle costs gives information and comparison on some of the different pavement types used in the country. The results of the feasibility study is that HMA is a less expensive option than surface dressing only when traffic is 4000 AADT or more and there is a 2.5% increase in traffic per year. The life-cycle costs of HMA and surface dressing are similar (cost of surface dressing / cost of HMA ≈ 90%) when traffic is 3000 AADT and with 2.5% increase in traffic per year or when traffic is 5000 AADT and there is 0% increase. When traffic volumes are lower than this the surface dressing is always a less expensive option. *[40]*

Stone Matrix Asphalt (SMA) has been used in Iceland but was not included in the feasibility study since it is mainly used for roads that carry the heaviest traffic volume (> 5000 AADT). Furthermore, it was assumed in the study that HMA's service life depends on studded tire wear and that surface dressing's service life depends on traffic volume.

The main drawback of the most commonly used pavement, the surface dressing, is the environmental impact caused by inorganic solvents (white spirit, a colorless liquid derived from petrol) in the cutback bitumen. *[40]* Experiments with bitumen emulsion in Iceland have not all been successful and it is guessed that some of the reasons may be uneven binder distribution and difficulties related to designing an emulsion that is suitable for unwashed aggregates which is what has been used for surface dressings with cutback bitumen. It is likely that use of bitumen emulsion instead of cutback bitumen will increase in the next years. *[45]*

Additives used in Iceland are primarily fibers for SMA production and anti-stripping agents, mainly amines, which are used to increase adhesion between the asphalt binder and the aggregate in the presence of moisture.

4.2.1.2 Methods

The Marshall mix design method is the customary hot mix asphalt design method in Iceland although it has been modified slightly to decrease moisture sensitivity, mainly by increasing the bitumen content. Only two bitumen grades are commonly used in Iceland, 70/100 and 160/220, which if classified according to the Superpave grading system would be comparable to PG 64-22 and PG 58-28, respectively. *[37]* According to information from the two largest asphalt plants in Iceland, Hofdi ltd. and Hladbaer-Colas ltd., the general hot mix asphalt production in Iceland can be described as follows.

Aggregates (which usually contain about 3-6% moisture) are dried at about 160 to 180°C (320 to 356°F). Dust and particulates are filtered from the exhaust air and later mixed with the asphalt. Diesel oil or fuel oil is used in the drying process but electricity in the rest of the production process. The bitumen, which is heated to about 150 to 160°C (302 to 320°F) is then mixed with the aggregates and finally the mixture is transported to a silo where it is kept at about 150 to 160°C (302 to 320°F) until it is loaded on trucks. *[46,47]* The asphalt is usually placed at about 130-140°C (266-284°F) and lift thicknesses are usually about 40-50 mm (1.6-2.0 in). *[40]*

Experience has shown that because of the frequent temperature oscillations around 0°C (32°F) during the winter and long periods of wet weather, low air voids is essential for good pavement performance. *[37]*

This moisture content, 3-6%, is relatively high and needs to be taken into consideration when estimating the fuel consumption reduction in WMA production. For example for the WAM Foam consumption reduction measurement in Norway in 2001 where a 31.5% reduction was measured, the average moisture in the aggregate before entering the drying drum was 2.3%. *[17]* In another report from the WAM Foam developers, a graph is given to evaluate the fuel consumption reduction that can be expected given certain moisture content in the aggregate. According to the graph, for a 4.5% moisture content the reduction in fuel consumption can be expected to be about 25%. *[13]*

4.2.1.3 Standard Specifications

The Road Administration issues Alverk '95, a general job description for road and bridge construction based on appropriate standards, such as ASTM, EN and ISO. Its purpose is to give coordinated regulations for construction, inspection and measurements for various types of projects. *[38]* A few of its requirements regarding HMA production and placement process are: *[48]*

- For mixing, the temperature of the binder must be according to Table 4.3:

Table 4.3: Mixing temperatures for hot mix asphalt production according to the Road Administration's Alverk '95.

	Pen40	Pen60	Pen85	Pen120	Pen180
Max. allowable temperature during mixing [°C (°F)]	205 (401)	190 (374)	175 (347)	165 (329)	160 (320)
Temperature during mixing under normal circumstances [°C (°F)]	180 (356)	170 (338)	160 (320)	155 (311)	150 (302)

When the mix is placed during cold weather the mixing temperature must be increased;

- percent air voids in the pavement must be below 3%. If two or more layers are laid, the air voids in the lower layer(s) must be below 6%;
- pavement placement is not allowed in rain or at lower temperature than 1°C (34°F) in calm weather and with increased wind this temperature limit rises;
- placement of a HMA surface course is not allowed after September 1st and base course not after October 15th, unless specially recommended. The start of the paving season is not specified with a date;
- the temperature of the mixture in the paver may not be lower than specified in the Table 4.4: *[48, bl. 59]*

Table 4.4: Temperatures for hot mix asphalt production at beginning of placement according to the Road Administration's Alverk '95.

Binder type	Pen40	Pen85	Pen180
Lowest allowable mixture temperature in the paver [°C (°F)]	165 (329)	145 (293)	135 (275)

- during transportation of the mixture, the truck bed must be intact and clean and the mixture must be covered; *[48, bl.57-59]*
- when the temperature of the new pavement has cooled to below 60°C (140°F) it can be opened to traffic. *[48, bl.58]*

4.2.1.4 Asphalt Plants

There are 9 asphalt plants in Iceland, all batch plants and 3 of them are portable. The 6 fixed location plants are at 5 different locations around the country. The ones that are in the greater Reykjavik area have a production capacity of 330 tons/hour altogether, the 3 portable plants can produce 200 tons/hour and the rest can produce 120 tons/hour altogether. In total that is a production capacity of 650 tons/hour.

If a 200 km (124 mi) distance is used as a maximum transportation distance from each plant, almost all road sections in the country with more traffic than 1500 AADT and most towns are within the service radius of the fixed location plants, and the portable plants are available for other areas. The feasibility study mentioned earlier discusses this and also states that a 200 km (124 mi) haul distance is realistic under good circumstances. A conclusion in the report is therefore that technically nothing stands in the way of using HMA where it is considered feasible. *[40]*

Chapters 3.2.1 and 3.3.1 discussed if and how asphalt plants need to be modified for the addition of Aspha-min zeolite and Sasobit wax, respectively. Strictly speaking, equipment modifications are not necessary for either method if the asphalt plant is equipped to add fibers to the mix, like is done in SMA production. Sasobit wax has been blended directly to the mix at the same time as fibers are added to SMA mix. *[9]* The producers of Aspha-min zeolite state that zeolite can be added by hand, with existing fiber addition equipment or through specially designed feeders. *[21]* In the NCAT study the zeolite was pneumatically fed into a drum plant at the same point as the asphalt cement, using an existing fiber addition line and using a vane feeder to control the addition rate. *[8]* As was mentioned earlier in this section, SMA has been produced in Iceland for roads with 5000 AADT and more. The greater Reykjavik area is the only place in the country that has such high traffic volumes to any extent and that is also where the largest asphalt plants are. SMA is produced at Hofdi ltd. and Hladbaer-Colas ltd. *[49,50]* and their asphalt plants therefore have the equipment to add fibers to the mix. Sasobit is available as small pellets, similar in size as some fibers, and therefore it should not cause any trouble to use the existing fiber addition equipment for it. The fiber addition equipment could also be used to add Aspha-min, but it is a very fine powder *[14]* and therefore it is possible that people might be more reluctant to use their fiber addition equipment for it than for the wax pellets.

Equipment modifications for the WAM Foam are more extensive. According to information from Kolo Veidekke in Norway the initial investment cost of the foaming device that needs to be installed varies greatly depending on how the asphalt plant is set up. *[51]*

4.2.1.5 Icelandic Research on Warm Mix Asphalt

A laboratory research on reduced asphalt production temperatures is currently being conducted in Iceland and is sponsored by the Road Administration's Research Fund. The project is still going on and a report has not been published yet. Two Icelandic aggregate types were used and four mix types; regular HMA, a mix with Aspha-min zeolite, a mix with Aspha-min zeolite plus an anti-stripping agent (Wetfix N) and a mix with Sasobit wax. All mix types were produced at 115°C (239°F) and 140°C (284°F) and compacted at about 5°C (9°F) lower.

Preliminary results indicate that Sasobit performs better than the Aspha-min mixes (with and without Wetfix) in terms of stability, deformation, percent air voids and moisture sensitivity. The mixes with Sasobit produced at 115°C (239°F) generally show a similar performance as the regular hot mix produced at 140°C (284°F) for all these factors. *[52]*

4.2.2 Environmental and Health Issues

In this section the environmental effects of asphalt production will be discussed in relation to environmental awareness and Icelandic pollution and health regulations.

Asphalt is the residuum produced by the distillation of crude petroleum which mainly consists of:

- Aliphatic compounds;
- cyclic alkanes;
- aromatic hydrocarbons;
- heterocyclic compounds containing nitrogen, oxygen and sulfur atoms;
- metals, e.g. iron, nickel and vanadium.

The exact chemical composition of asphalt depends on the chemical complexity of the original crude petroleum plus the manufacturing processes. Consequently, no two asphalts are chemically identical. *[11]*

4.2.2.1 The Kyoto Protocol

An amendment to the United Nations Framework Convention on Climate Change was negotiated in Kyoto in 1997 and came into effect on February 16, 2005. This is the so-called Kyoto Protocol. Countries that ratify this protocol, including Iceland, commit to reducing their collective emissions of six greenhouse gases by 5.2% compared to the year 1990, calculated as an average over the five year period of 2008-2012. The participating nations were expected to have reached noticeable success in 2005. Conditions in each country were considered when national targets were set and they range from 8% reductions for the European Union to 10% permitted increases for Iceland.

It is difficult to set similar national targets for Iceland as for larger nations because of the smallness of the economy and the composition of the emissions. What causes the difficulty is the relative influence of individual projects on the overall emissions in the country. According to the Protocol the national targets for Iceland are twofold: First, overall emissions from greenhouse gases can not increase more than 10% from 1990, i.e., must be less than 3100 thousand tons carbon dioxide yearly on average from 2008 to 2012. Second, carbon dioxide from new heavy industry after 1990 can not exceed 1600 thousand tons yearly on average from 2008 to 2012. *[53]*

About 70% of Iceland's energy consumption is from domestic sustainable energy sources, i.e. hydro-electric or geothermal power plants. The remaining 30% is mainly imported fuel for cars and ships. *[54]* It is therefore evident that Iceland's role in the international agreement to reduce emission of greenhouse gases is based on other prerequisites and methods than in the majority of the other participating countries.

4.2.2.2 Laws and Regulations in Iceland

Icelandic legislative act nr. 7/1998 on hygienic and pollution control contains regulations for polluting industry and activities and pollution limits for various pollutants. Article nr.

5 states that all business activities that can entail pollution need an operational license and that guideline limits for air quality, pollutants and their disposal are set. Regulation nr. 787/1999 states that air pollution should be kept at minimum to maintain the quality of clean air. It also says that any polluting business activity shall take appropriate measures to inhibit air pollution and use the best available technique to do so. The regulation also lists the air pollutants that need to be considered when evaluating and controlling air quality. The air pollutants that are to be investigated first are:

- Sulfur dioxide (SO_2);
- Nitrogen dioxide (NO_2);
- fine dust, e.g. soot (including PM_{10});
- Particulate Matter;
- Lead;
- Ozone;
- Benzene.

Other air pollutants of concern are carbon monoxide (CO), aromatic hydrocarbons, cadmium, arsenic, nickel and mercury.

Regulation nr. 251/2002 is about sulfur dioxide, nitrogen dioxide, nitrogen oxide, benzene, carbon monoxide, particulate matter and lead in the atmosphere and public information. The goal of the regulation is to set limits for these materials and ensure that satisfactory and coordinated measurements of these materials are conducted and made available to the public. It sets two main types of limits; environmental limits and alarm limits. *Environmental limit* is the maximum allowed value of pollution in a certain receptor based on scientific knowledge in order to prevent or decrease harmful influences on people's health and/or the environment. *Alarm limit* is a limit such that if exceeded, people's health is at risk because of pollution even if it's only temporary. A warning must be sent out and appropriate measures must be taken if there is a risk that this limit will be exceeded. Tables for these limits for a few pollutants are in Appendix A. Of special interest in those tables is that the environmental limits for particulate matter (PM_{10}) and benzene (C_6H_6) are supposed to gradually get stricter in the next years, until 2010.

4.2.2.3 Operational Licenses

The Environmental and Food Agency in Iceland issues operational licenses to companies that can entail pollution. Hot mix asphalt plants, both portable and fixed location, need an operational license. According to legislative act nr. 7/1998 all asphalt plants with a fixed location must give yearly reports about a "Green accounting". *[55]* The objective of Green accounting is to make companies provide information to the public and authorities about how they are dealing with environmental issues and to encourage companies to monitor the environmental aspects of their activity and watch for new developments.

One of the requirements for operational licenses for asphalt plants is that air from the burner in the aggregate dryer be cleaned with a filter and that the exhaust air may not include more particulates than 100 mg/Nm^3. *[56]* Figure 4.1 shows this limit and three measurements from two asphalt plants for the years 2003 and 2004.

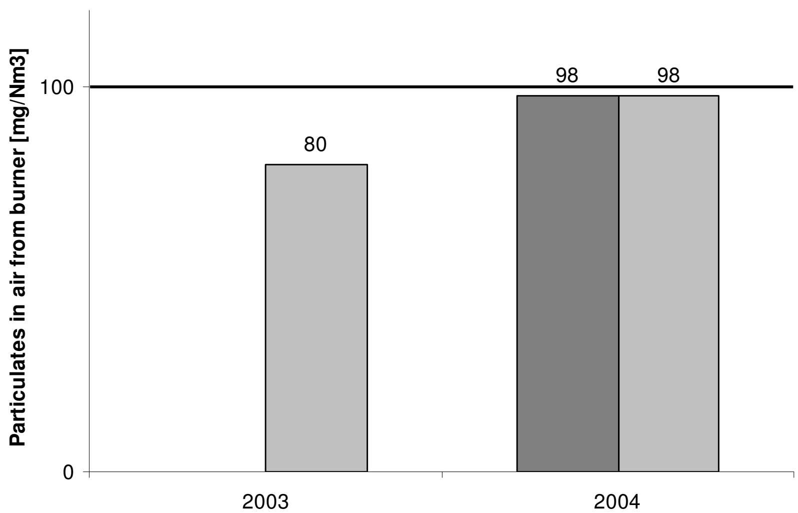

Figure 4.1: Three dryer exhaust air measurements from two asphalt plants in Iceland for the years 2003 and 2004. The black line shows the requirements limit necessary for plants to be below. *[46,57]*

As mentioned earlier, some environmental limits are supposed to get gradually stricter over the next few years. If the same development will occur in the future for limits for the particulates from the aggregate drying, it looks like asphalt producers will have to make some arrangements to decrease the particulates in the exhaust air.

Hofdi ltd. is the only asphalt plant that reports measurements of other pollutants in its Green accounting. Table 4.5 shows their measurements.

Table 4.5: Pollutant measurements from Hofdi ltd. for 2003 and 2004. *[46]*

	2003	2004
NO_x [mg/Nm^3]	26	5
CO [mg/Nm^3]	88	54
HCl [mg/Nm^3]	3	<0.9

4.2.2.4 Energy Consumption

As discussed in section 4.2.1.2, approximately 25% reduction in energy consumption could be expected when using WMA methods with Icelandic aggregates. In Iceland, diesel oil or fuel oil is usually used to heat and dry the aggregate and then electrical power is used for the rest of the production process. Generally, about 8-10 liters of diesel or fuel oil and 8-14 kWh of electricity are used to produce one ton of asphalt. *[55]* Since electrical power in Iceland comes from domestic sustainable energy sources (hydro-electric and geothermal power plants) the environmental effects from the energy consumption used in the production process is not as severe as where only fuel oil is used in the whole process. But the energy consumption reduction in the warm mix processes is in the oil driven drying process and therefore this reduction is just as important for Iceland as for most other countries.

4.2.2.5 Environmental Issues Summary

Today, pollution from asphalt plants in Iceland is within limit boundaries set by authorities. But some pollution limits in Iceland are starting to get stricter, although not at a similar pace as for most other countries participating in the Kyoto protocol. It is therefore timely for the asphalt industry to follow environmentally friendly developments and test new technologies and adopt those that suit Icelandic conditions.

Although energy sources in Iceland are primarily domestic sustainable energy sources (hydro-electric and geothermal power plants), diesel oil or fuel oil is used for the part of the production process where the warm mix’s energy consumption reduction occurs. The energy consumption reduction is therefore as important for Iceland as for most other countries.

There do not seem to be any issues with occupational health and safety regulations in Iceland related to asphalt production or paving. In that sense, WMA would mainly be beneficial for improving general working conditions by reducing unhealthy fumes and odors.

The finding in the NIOSH review discussed earlier, i.e. that studies indicate significant changes in pulmonary function in 1 of 44 workers engaged in open-air asphalt paving but in 3 of 9 workers engaged in underground asphalt paving, is interesting for the paving industry in Iceland. In the 13,000 km (8080 mi) long highway system in Iceland there are 8 road tunnels, in total about 30 km (20 mi), and 3 more tunnels have been authorized or are already under construction.

The environmental benefits of the reduced pollution from WMA would be most beneficial in the most densely populated area in Iceland, i.e. the greater Reykjavik area, and for special projects like underground paving.

From an environmental point of view, the warm mix technologies would definitely be beneficial for Iceland but it is impossible to predict if or when incentives or regulations will make them economically beneficial for the asphalt producers and buyers.

4.2.3 Economical Issues

In this section a cost comparison is made between traditional hot mix asphalt production in Iceland and the three WMA methods; WAM Foam, Aspha-min zeolite and Sasobit wax. The reduction in fuel usage to produce WMA can decrease the cost of transportation construction projects, but there is also additional cost involved in equipment modification and royalty (WAM Foam) and the use of additives (Aspha-min zeolite and Sasobit wax).

According to information from Kolo Veidekke there is nothing in the WAM Foam production process itself that will increase the cost compared to hot mix asphalt. It is possible to maintain the same plant capacity as for hot mix production and no additives are used in the process. There is however an initial investment cost in installing the foaming device which can vary greatly depending on how the asphalt plant is set up. For fairly new plants, control systems can normally be modified quite easily. To give an idea, Kolo Veidekke has had costs of about $30,000-40,000 for plant modifications. *[51]*

There is also a royalty for using the method, first an up front fee of $15,000 per company and then a fee of $5000 per plant per year. Also, after a free first year there is a royalty of 30 cents per ton produced (starting to run after the value is above $5000). *[16]*

Savings in fuel consumption for WAM Foam are in the drying process where the documented savings are about 30%. This has been measured in both oil (diesel) and gas (propane/butane) driven plants. *[51]*

According to information from the developers of Aspha-Min zeolite, the extra cost when applying Aspha-min zeolite in Europe is about 2 to 3 EUR per ton. It has to be shipped from Europe to Iceland, so shipping rates are a large part of the price calculation for the Icelandic market. *[58]* Using January 2006 currency exchange rates the price in Europe is similar to about $2.40 to $3.60 per ton. Detailed price information for Iceland were not given but according to information from Hubbard Construction Company in Florida the price in the USA is $1.32 per kg ($0.60 per pound), which at the recommended dosage 0.3% of mix weight i.e. 3 kg per ton (6.6 lbs per ton) would be $3.96 per ton of mix. *[59]* It will be assumed here that the price in Iceland is similar to the price in the US although it is very likely to be higher because of smaller purchase volumes in Iceland. Customs clearance, excise tax and transport from port to plant in Iceland are assumed to be approximately $0.02 per kg of Aspha-min (based on shipping about 40,000 kg per shipping container). *[60,20]* Adding this up gives approximately $3.96 + $0.02 per kg × 3 kg ≈ **$4.00 per ton** of asphalt produced for adding Aspha-min zeolite.

Sasol Wax gave a price range estimate of about 1.75 to 2.00 EUR per kg delivered at an Icelandic port, depending on the volume of purchase and the cost of shipping. Using January 2006 currency exchange rates this is similar to about $2.10 to 2.40 per kg. The price in the USA was given as $1.72 per kg ($0.78 per pound). *[33]* The recommended use of Sasobit wax is 3% by weight of total binder. For a mix with 5% binder by weight, the amount of Sasobit needed is about 1.5 kg for a ton of mix. Customs clearance, excise tax and transport from port to plant in Iceland are assumed to be approximately $0.08 per kg of Sasobit (based on 720 kg per pallet and shipping approximately 12,000 kg per shipping container). *[60,23]* Adding this up gives approximately $2.33 per kg × 1.5 kg ≈ **$3.50 per ton** of asphalt produced for adding Sasobit wax.

In the following calculations for cost of energy consumption, a 25% reduction in consumption will be used for all three WMA methods, according to the discussion in chapter 4.2.1.2. For all three methods the energy consumption reduction is in the aggregate drying process and in Iceland diesel oil or fuel oil is generally used for the drying. According to information from asphalt plants in Iceland, approximately 8-10 liters of oil are used to produce one ton of mix. The price in Iceland for diesel oil for industrial companies is $0.7 per liter (without value-added tax and using January 2006 currency exchange rates). *[61]* For the rest of the production process, asphalt plants in Iceland usually use electricity, approximately 8-14 kWh to produce one ton of asphalt. In Reykjavik the price of electricity to companies is $0.02 per kWh during the summer. *[62]* For example, for one ton of HMA the average energy cost is: (9 liters × $0.7 per liter) + (11 kWh × $0.02 per kWh) = $6.5.

A typical total cost for a ton of hot mix asphalt in Iceland is $89 per ton (5400 kr/ton) if domestic aggregates are used and $98 per ton (6000 kr/ton) with imported aggregates. *[40]*

These cost calculations are all summed up in Table 4.6.

Table 4.6: A cost comparison of traditional hot mix asphalt production in Iceland and the three WMA methods, WAM Foam, Aspha-min zeolite and Sasobit wax.

	HMA	WAM Foam	Aspha-min zeolite	Sasobit wax
Additional cost per ton of mix [$]	-	0.3	4.0	3.5
Cost of energy consumption per ton of mix (oil + electricity) [$]	6.5	4.9	4.9	4.9
Reduction in energy cost compared to HMA [$]	-	1.6	1.6	1.6
Calculation for total cost per ton [$]	-	89 + 0.3 - 1.6	89 + 4.0 - 1.6	89 + 3.5 - 1.6
Total cost per ton [$]	**89**	**87.7 ***	**91.4**	**90.9**
% increase or decrease	**-**	**- 1.5% ***	**+ 2.7%**	**+ 2.1%**
Installation cost and royalty [$]	-	45-55,000 (+ 5000 per year)	-	-
Example: A 30,000 ton production in a beginning year [$]	*2,670,000*	*2,677,000*	*2,742,000*	*2,727,000*
Example: A 30,000 ton production per year (after first year) [$]	*2,670,000*	*2,631,000*	*2,742,000*	*2,727,000*

* These number do not include the installation cost and royalty.

In the last two lines of the Table 4.6 an example is given for a 30,000 ton production, which is similar to the amount of HMA that the Road Administration uses for maintenance in one year. According to the calculations in Table 4.6, it takes approximately 40,000 tons of WAM Foam mix production to pay off the initial royalty and installation cost for the WAM Foam equipment.

It should be noted that possible equipment modifications for Aspha-min or Sasobit are not included in the calculations. Their magnitude and cost and if they are at all needed depends on each individual asphalt plant and is therefore difficult to evaluate.

From Table 4.6 it can be seen that WAM Foam appears to be least costly of all the three warm mix methods and Aspha-min zeolite appears to be the most costly method.

Total HMA production in Iceland is about 250,000 tons per year. Although not realistic speculations, it is interesting to calculate what these numbers mean for the country's total asphalt production. A reduced cost for energy consumption of $1.6 per ton gives approximately a $400,000 reduction in oil cost for the whole country. A 25% oil consumption reduction means approximately a 560,000 liter reduction in oil usage per year. Finally, $2.40 or $1.90 increase in cost per ton for the zeolite or wax additives respectively (after energy consumption reduction has been taken into account), is approximately a $600,000 or $475,000 increase in total asphalt production cost per year for the whole country, respectively.

4.2.4 Summary

The length of Iceland's highway system is about 14,000 km (8,700 mi) and thereof about 5,500 km (3,420 mi) are paved. Surface dressing is the most common pavement type and HMA is only used where traffic reaches 3000 AADT. Total HMA production per year in Iceland is not known precisely, but for an average year it can be assumed to be about 250,000 tons.

Two characteristics of the Icelandic climate are especially important for pavement design; a relatively small variation in temperature over the year and frequent temperature oscillations around 0°C (32°F) during the winter. Experience has shown that because of the frequent temperature oscillations and long periods of wet weather, low air voids are essential for good pavement performance.

A laboratory research about reduced asphalt production temperatures using Aspha-min zeolite and Sasobit wax is currently being conducted in Iceland. A report has not been published yet but preliminary results indicate that the Sasobit mixes perform better than the Aspha-min mixes (with and without anti-stripping agent) in terms of stability, deformation, percent air voids and moisture sensitivity. The mixes with Sasobit produced at 115°C (239°F) generally show a similar performance as the regular hot mix produced at 140°C (284°F) for all these factors.

Today, pollution from asphalt plants in Iceland is within limit boundaries set by authorities. But some pollution limits in Iceland are starting to get stricter, although probably not at a similar pace as for most other countries participating in the Kyoto Protocol. It is therefore timely for the asphalt industry to follow environmentally friendly developments and test new technologies and adopt those that suit Icelandic conditions.

Although energy sources in Iceland are primarily domestic sustainable energy sources, oil is used for the part of the production process where the warm mix's energy consumption reduction occurs. The environmental benefits of the reduced pollution from WMA would be mostly beneficial in the most densely populated area in Iceland, i.e. the greater Reykjavik area, and for special projects like non-open air paving. From an environmental point of view, the warm mix technologies would definitely be beneficial for Iceland but it is impossible to predict if or when incentives or regulations will make them economically beneficial for the asphalt producers and buyers.

From Table 4.6 it can be seen that according to the given information, the WAM Foam method appears to be the least costly one of all three warm mix methods, but it takes approximately a 40,000 ton production to pay off the initial installation cost and royalty. The Aspha-min zeolite appears to be the most costly method, increasing the cost per ton by approximately 2.7% while Sasobit wax increases the cost by approximately 2.1%.

4.3 SURVEY

4.3.1 Description of Method and Participants

In order to evaluate WMA's actual potential in a real market environment and in cold weather conditions, a survey was conducted among professionals in the paving industry in Iceland. The survey consisted of 17 questions which were either generally about current paving practices in Iceland or about WMA and the respondent's opinion on its potential and applicability for Icelandic conditions.

The paving industry in Iceland is a relatively small market and because of Iceland's geographical location it is relatively isolated. It is therefore an ideal place to do a survey among professionals to get a good overall idea of a market's receptivity. In total 10 responses were received from the 12 questionnaires that were sent out to professionals from various sectors of the paving industry; designers, producers, a contractor, researcher, teacher and professionals from the Icelandic Road Administration. The breakdown of the respondents between sectors is as follows:

- 2 are professionals from the Road Administration;

- 2 are professionals from asphalt production firms;
- 2 are engineers from consultant engineering firms;
- 1 is a professional from a contracting firm;
- 1 is a researcher from a research institute;
- 1 is a teacher at the University of Iceland;
- 1 is from a company that imports asphalt additives.

It must be noted that all the respondents participated in this study as individuals and therefore their answers do not represent their companies' opinions in any way. Their professional positions are only mentioned to try to evaluate how various issues related to WMA may appear differently to different sectors within the paving industry.

The sample size used for the survey is not large but neither is the Icelandic paving industry. By choosing participants from the various sectors of the industry, the results give a good overall idea about WMA's potential and people's main concerns regarding WMA in the cold weather conditions in Iceland.

The complete list of questions as delivered to the respondents and a summary about WMA that was sent with it are showed in appendix B and the answers from all respondents, translated from Icelandic as directly as possible, are in appendix C.

4.3.2 Survey Results

Following are summaries of the responses for each of the 17 questions. The surveys were conducted in Icelandic and therefore all questions and answers are translated.

Question 1: What do you think are the most common problems that arise during paving in Iceland?

Nine out of the 10 respondents mentioned **weather conditions.** Five of them specifically mentioned cold and wet or changeable weather conditions during transport and/or placement, i.e. anything that contributes to cooling the material too much and affecting viscosity, workability and quality.

Two respondents mentioned **temperature differentials** because of placement of cooler portions of the material mass and transverse screed marks, ugly joints and visible handwork were also mentioned. Relatively short paving season resulting in short-term recruitment of workers and problems related to drying of aggregates during production in rain were also mentioned.

Three respondents mentioned **long haul distances,** either directly as a contributor to cooling of the material or, as a result of the thin population and too few asphalt plants, a limiting factor to the usage of hot mix asphalt more widely around the country.

Four respondents mentioned **lack of good aggregates.** One of them more specifically mentioned these three as common problems; lack of aggregates with defined gradation (within stringent boundaries), lack of aggregates with good toughness and abrasion resistance, and moisture in the aggregates because of porosity, but also mentioned that these three factors have been improved in the last years by importing aggregates. Aggregate segregation was also mentioned.

Other problems mentioned were defective and outdated asphalt plants at some locations, insufficient groundwork and wear because of studded tires (a cause for pavement maintenance).

Question 2: Which of these problems do you think are the most costly ones?

Four respondents said that it would be problems related to **weather**; low air temperature, changeable weather, etc. **Short paving season** was also mentioned and high fixed cost in equipment and workers training because of it. Two respondents mentioned the cost of using low quality pavement (e.g. due to insufficient compaction) that will have a **shorter service life** and repair of low quality areas in the pavement was also mentioned. Other factors mentioned were; throwing away material because it has become too cold; moisture in the aggregates resulting in high drying cost; wear because of studded tires and few good aggregates.

Question 3: What do you think are the most limiting factors for quality and durability of pavements in Iceland (for example regarding mix quality, distress, environmental factors)?

Eight of the ten respondents mentioned **studded tire wear**, three of them as the only limiting factor but the others mention it along with other factors.

Five respondents mentioned **poor aggregate quality**, either as insufficient toughness and abrasion or lack of homogeneity which can affect the drying process, amount of binder needed and other factors that affect service life and workability.

Five respondents mentioned **weather conditions**, e.g. moist climate, many freeze-thaw cycles during the winter (especially in the southwest part of the country) and the effect weather has on the need for compaction and on compaction practices.

Two respondents mentioned **salt** applications, which are common in urban areas. Other factors that were mentioned are aging characteristics, bad practices during placement that result in damages.

Question 4: How familiar were you with warm mix asphalt before you read the attached summary?

a) Never heard of it before b) Very little c) Fairly much d) Very much

Nine of the respondents answered this question, 1 had never heard of it before, 4 were very little familiar, 3 fairly much and 1 very much familiar with WMA.

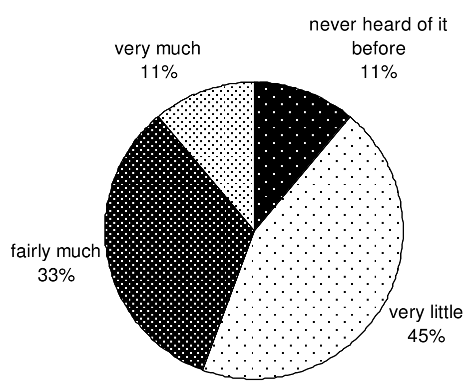

Figure 5.1: Answers to question 4.

Question 5: What do you think are the main benefits of warm mix asphalt?

Reduction in energy consumption was mentioned by 6 respondents. However, 2 respondents expressed the following concerns about the temperature reduction issue.

- "Other things being equal, the energy reduction is most important. However, the question is whether the energy reduction is realistic because the aggregates need to be heated to high temperatures to dry quickly since Icelandic aggregates are usually porous and contain much water, compared to what is common in the other Nordic countries."
- "Reduction in energy consumption during production is a factor that will be used to evaluate the benefits of WMA if it will lower the overall cost of a project. If additives cause an increase in the overall cost of a project, WMA does not have a chance on the market. The largest HMA buyers, i.e. the Road Administration and the City of Reykjavik, are not ready to value improved environmental effects. That will not be done until regulations will be set that must be followed."

Four respondents mentioned **lower emissions** or lower environmental impact, thereof one specifically mentioned lower environmental impact in urban areas and that being more relevant though in most other countries than Iceland.

Four mentioned **longer haul distances** and one specifically mentioned the possibility of paving at locations that are too small to take a portable asphalt plant to and too far away from fixed location plants for safe haul distances. One more indirectly mentioned longer haul distances and easier compaction by giving this answer:

- "If the mix will be more workable at lower temperatures it can help with many of the problems mentioned in question 1. However, the question is whether the temperature loss will remain the same so that people will continue to have the same problems, just at lower temperatures. Would it be possible to continue to produce at high temperatures but increase the time available to finish the paving process? If so, the benefits of reduction in energy consumption and a cleaner production will recede."

Other answers were; easier compaction (especially for SMA with a hard binder, pen <100 which is rather cumbersome during placement), the possibility of placement at a lower temperature, more suitable for Icelandic weather conditions, and allows longer paving season.

Question 6: What do you think are the main drawbacks of warm mix asphalt?

Six of the respondents showed some concern about **lack of information about long-term performance**, i.e. whether same quality can be reached as for regular HMA, and did not want to give a more definite answer. One specifically doubted that foaming methods like the one described in the summary would be comparable to regular HMA, regarding service life, mixture homogeneity, adhesion between binder and aggregates and loss of aggregates from the pavement surface.

Three respondents mentioned the usage of **additives that incur moisture**.

- "The usage of additives that incur moisture (the zeolite, foamed bitumen and everything that can actuate absorption in the mix because it might affect the adhesion between the binder and aggregate)."
- "The possibility of incomplete drying of aggregates that causes the water that will be left on the aggregate to freeze during the first winter. Icelandic aggregates are relatively porous and contain much water and lower mixing temperatures may not be sufficient to fully dry them."
- "Regarding the zeolites it is important to consider the effects of the water that is released during production, considering Icelandic weather conditions."

Four respondents mentioned that if there is **increased cost** then that is a drawback. Two respondents mentioned **lack of experience** with WMA that could cause initial difficulties and finally, two mentioned **increased difficulty or complexity** (because of additives and/or equipment) in the production and placement processes.

Question 7: Do you think the paving industry in Iceland will benefit from using warm mix asphalt? If so, in what way mainly?

Six respondents answered with a **yes**; the industry in Iceland would benefit. Two answered with a yes but only if at least the same quality can be reached and energy consumption and emissions can be lowered.

Four of the six positive respondents mentioned the **reduced pollution and energy consumption** to be a benefit and one especially mentioned that requirements for environmental issues can become more significant in the future. Two mentioned the possibility of **increased haul distances** and two mentioned the **lower placement temperature**. Other things mentioned were the possibility of extended paving season and that workers protection issues might encourage WMA usage.

Two respondents were **doubtful** that the industry would benefit.

- "At present I doubt it. First, there would have to be some experiments conducted to see if WMA will be all right in Icelandic conditions (many freeze-thaw cycles, rainy weather). Second, whether it pays off needs to be checked. Also, soft bitumen (pen 150-200) is used a lot in Iceland and it is quite workable during placement under normal circumstances. But the energy savings is positive, also lower environmental impact, and probably the paving season could be extended but paving late in the fall has worked tolerably as long as the weather stays dry. Then days of fair-weather are used to pave the streets with the heaviest traffic and local streets are paved later in the fall."

- "I do not believe that the words "environmental awareness" are dominant enough in the paving industry in Iceland today for WMA to be accepted. Especially if there is not a cost reduction and no certainty for at least the same service life."

Question 8: If WMA would be produced in Iceland, which of the methods that are mentioned in the following summary (foam, zeolite, wax), do you think would be most likely to be chosen? Why?

Four respondents guessed that either **Aspha-min zeolite or Sasobit wax** additives would be the most likely methods and three thought that it would be **WAM Foam**. Three did not give a definite answer.

Those that mentioned the zeolite and wax methods did not use the same reasoning. One said that they are most likely to be looked at first because they are currently being tested in Iceland. Other reasons were e.g. that WAM Foam is patented, seems to have the most complicated and delicate equipment and water in a pipe to the mixer or into the bitumen is more difficult e.g. because of frost problems.

Two of those that think WAM Foam is more likely, mention as a reason that it has been tested in Norway and the paving industry in Iceland, especially the Road Administration, often goes with what gives good results in the other Nordic countries. Two mention that foamed bitumen has been used for base stabilization in Iceland for years with good results so there is experience with that. One mentions that the least expensive method always looks best to the buyers and therefore WAM Foam would be chosen.

Question 9: If warm mix asphalt would be used in Iceland, where in the country (for example, greater Reykjavík area or rural areas, north or south part of the country) do you think it would be most suitable?

Six respondents wrote it would probably be **outside of the greater Reykjavik area**. Three of them specifically mentioned places outside of the greater Reykjavik area that are too far away from the nearest asphalt plant (i.e. more than 200 km or a 2 hour drive).

Five respondents wrote **in and/or around the greater Reykjavik area**. Reasons mentioned were because the largest and best equipped asphalt plants and most qualified workers are there, elsewhere there is not enough traffic for WMA to be chosen, and because pavement innovations are usually first tested in that area.

Two respondents wrote that WMA could be used **everywhere** in the country and one wrote that it could be recommended that this method be used for paving **in tunnels** to reduce pollution during the placement itself to improve the working environment.

Question 10: If warm mix asphalt would be used in Iceland, for what type of projects (for example concerning traffic load, population density, time of year) do you think it would be most suitable?

Five respondents wrote that it would more likely be used for less densely populated areas, i.e. **low traffic volumes** (e.g. outside of the largest towns and on the country's highway system) and three of them also wrote during **fall and spring**. One respondent wrote during the summer. Other responses were:

- "In my opinion there are two options. First, as a binder for SMA with a hard binder (pen <100) and second, during cold conditions (cold weather and thin lift that cools quickly, placement on a frozen base)."
- "There are indications that the wax may increase the pavement's capacity and therefore it might be an option on wharfs and other locations with heavy loads."
- "It is probably best to choose projects where studded tire wear is not a key factor in the pavement's service life. Projects like that could be where there is a lot of truck traffic. Furthermore, WMA could be tested as a base layer where the surface course (regular HMA) is laid one year later."
- "My hope is that WMA will be used as a stabilizing mass for the highway system and as a maintenance pavement for main roads in towns that are far away from asphalt plants."

Question 11: How much do you think a difference in cost between warm mix asphalt and traditional hot mix asphalt matters for WMA's potential in Iceland? In other

words, do you think it will be considered an option only if it costs less or as much or could it also be an option if it costs more?

Four respondents wrote that they thought WMA would **only be an option if it costs the same or less** than traditional HMA. Two of them specifically mentioned that it could not cost more unless authorities will require it to be used or set some emission restrictions.

Five respondents wrote that it could cost more but most of them agreed that the increase could only be moderate (one said 5-10%) and/or only if it will improve quality (or make it possible to pave in colder weather or transport the mix longer distances and make it an option at more locations than today).

One respondent wrote that WMA will only be an option if its total cost is lower than for regular HMA.

Question 12: Do you think that the equipment modifications that need to be done to produce WMA will decrease its potential for implementation?

Five of the respondents answered **no**, the equipment modifications should not be an issue.

Three answered **yes** in some way, one thinks it will likely decrease interest, one wrote that it might stop the whole thing and one wrote that it is unlikely that anyone will do the modifications unless public funds for experimental projects will pay for it or if an increased market is foreseeable.

Two wrote that it would depend on the modifications or whether WMA will be adopted.

Question 13: Do you think this lower mixture temperature will significantly affect factors like the length of the paving season, material transport from the plant to the site and the time from paving until traffic is allowed on the road? How much do you think factors like these matter when choosing paving methods in Iceland?

Three respondents simply answered with a **yes**. Four wrote that mainly **haul distances** would be affected which is important when choosing a method outside of the greater Reykjavik area. One mentions that the most influential factor is the length of the paving season.

One respondent wrote that WMA would not affect these factors and added: "I do though suspect that foamed asphalt is more sensitive to low air temperatures and rain than regular asphalt. I have noticed this during base stabilizing with foamed bitumen."

Another answer was that the paving season is not so much dependent on temperature, and asphalt mix has been transported very long distances (Reykjavik-Kirkjubaejarklaustur, Reykjavik-Hvammstangi) and placed with acceptable results but good days are chosen for such projects.

Two respondents wrote that **nowadays paving is done all year round in Iceland** but one added that the same quality is probably not reached when paving during frost.

Question 14: Do you know if there is anything being done in the paving industry in Iceland today that is similar to these warm mix asphalt processes in some way?

There is a laboratory research being conducted with Aspha-min zeolite and Sasobit wax at Hofdi for the Road Administration's Research Fund that will probably end with building a test section. Five of the respondents knew about that research and mentioned it in their answer. Three did not know of anything similar to WMA being done.

Two respondents mentioned that some work has been done with cold mixes based on **bitumen emulsion** in surface dressing but probably not in asphalt and that the results have not all been good. Finally, one mentioned **base stabilization with foamed asphalt** which has been successful, but is produced on site, not in a plant.

Question 15: What do you think would be the next steps in investigating the potential for implementation of warm mix asphalt in Iceland?

Most respondents agreed on that the next step is to **place test sections**. Two mentioned doing a cost-benefit analysis and one mentioned to take a good look at other countries' experience regarding wear.

Question 16: What is your general opinion so far on warm mix asphalt?

Seven of the respondents were positive, found it to be an interesting option and worth while to look into. One especially mentioned it as an interesting option because of environmental issues and if it will allow longer haul distances and placement at lower temperatures than before and one wrote it was promising regarding increased usage of asphalt in rural areas.

One respondent did not give a definite answer and two were somewhat negative regarding WMA's future. Their answers were:

- "Conducting some research on WMA under Icelandic conditions is positive but I am very doubtful about its future considering the way things are here."
- "Not bad as such. But it is clear that no one embraces new methods because people know what they have but not what they will get. Those that are in charge of these things in Iceland are willing to experiment but not in large steps and even if research results are good people still need to be convinced that a method is desirable etc."

Question 17: Is there anything else that you would like to mention?

The answers to this final question were the following:

- "[…] we do have some trouble with surface dressings, bleeding tends to occur during hot periods because the binder is soft and mixed with white spirit. Maybe this could be improved by mixing the binder with wax like is done in the Sasobit method; keep it soft above 60-80°C (140-176°F), but stiffer than regular surface dressing binder below that. If I remember correctly I was once taught that wax is not preferable in asphalt binders because of contraction/thermal cracking during frost. Here there is rarely much frost and the surface dressing binder is soft and perhaps there is not much risk that wax will spoil that sort of a binder. Perhaps it would also be possible to lay surface dressing in a colder weather than otherwise if the binder would be mixed with wax. It does though cool very rapidly after it is sprayed on the road which is not good. But this could be looked into more closely. It is also interesting to be able to lower emissions during placement. I have heard that workers have complained about SMA modified with EVA (Ethyl-vinyl-acetate) (it was laid on a test section in Reykjavik 10 years ago)."
- "This process must be worked on slowly but steadily because mistakes can ruin good ideas."
- "It is likely that the largest pavement buyers, i.e. the City of Reykjavik and the Road Administration, will primarily control whether matters like these develop in Iceland. If these parties will start to put more emphasis on environmental issues or see some other benefits in using WMA, the method will prevail here."
- "Modified binders have been used on very few occasions and SBS and EVA modified binders have increased durability but at the same time the job mix formula was changed so it is difficult to see which factor contributed to the increased durability."

- "Considering previous experience with full depth experiments here, I do not expect WMA will be tested here until some experience will be reached abroad. Anything could happen through international cooperation and Hladbaer-Colas is a part of a large multinational company in road construction."

4.3.3 Survey Discussion

Four out of nine respondents were fairly or very much familiar with WMA. Two of those are the asphalt producers, one is from the Road Administration and one is a contractor. This indicates that professionals in the industry generally watch for new technologies and especially the asphalt producers themselves.

There is obviously an agreement that weather conditions cause the most common and most costly paving problems in Iceland and many also mentioned it as one of limiting factors for pavement durability. All such weather related issues are important for WMA considerations. There was an obvious agreement that studded tire wear is the most limiting factor for durability and about half of the respondents also mentioned lack of good aggregates as a cause for common problems and limiting for durability. Those two most limiting factors for pavement service life are both factors that WMA does not really affect in either a good or bad way. Strictly speaking, WMA could therefore not help with those common pavement service life problems in Iceland.

Six of the respondents mentioned the energy reduction as the main benefit of WMA. But three respondents were doubtful of how beneficial it would really be in practice. It is interesting to take a look at who bring up those three comments. A researcher doubts that the reduced drying temperature will sufficiently dry the porous Icelandic aggregates. A contractor doubts that any of the possible benefits of WMA will matter unless WMA decreases overall costs of projects. A producer brings up some questions about the temperature gap between production and compaction and implies that perhaps it would be more beneficial to use WMA to increase the gap rather than to lower production temperatures. Longer haul distances were mentioned more often than lower emissions as main benefits. Also, various other benefits accomplished by using WMA as a compaction aid were mentioned, e.g. placement at lower temperatures and a longer paving season. Some of these issues can be improved by using the WMA methods at lower production temperatures, but according to many of the answers, people might find it desirable to rather use WMA methods at, or close to, HMA production temperatures in certain situations. Reaching sufficient compaction is very important for cold weather paving and because of the frequent temperature oscillations around 0°C (32°F) during the winter in Iceland and long periods of wet weather, low air voids is especially important and essential for good pavement performance. For example, the Road Administration specifies that percent air voids should be below 3%. It is therefore not surprising that considerations about using warm mix methods to increase compactability at lower temperatures came up repeatedly (e.g. lengthen paving season and increase haul distances).

When asked about WMA drawbacks, the majority of the respondents showed concern about the lack of information available about quality. This is understandable because WMA is a relatively new technology and there is not really much known about long-term quality and durability. According to the three answers about moisture, people are worried about the water from the zeolite and the foamed bitumen which might affect the adhesion between the binder and aggregate, and the possibility of insufficient drying of the aggregates. Moisture susceptibility is a common problem for cold weather paving and these thoughts confirm that moisture susceptibility is an important issue when using WMA in cold weather conditions and it is of special concern when using Icelandic aggregate because of how porous they are. This indicates that people might be skeptical about lowering production temperatures as much as the WMA methods allow.

Most of the respondents agreed that WMA would have a significant impact on some key problem areas in Icelandic paving, primarily haul distances. According to some of the answers, WMA would not lengthen the paving season since paving is done all year round nowadays but it might increase the quality and workability of the mix for those winter paving projects.

According to many of the answers from the professionals from the Road Administration, haul distances are an important issue in Iceland. For example, both of them mentioned too long haul distances as a common problem in Iceland and mentioned increased haul distances as a main WMA benefit and also when they were asked about their general opinion on WMA. Haul distances were repeatedly mentioned by other participants as well but since the Road Administration is in charge of the majority of the county's road system, it is of special interest to see what is important to its professionals. Furthermore, both of them discuss that environmental regulations may become stricter in the future and even though most of the other participants mentioned the environmental issues as benefits, none of them specifically mentioned the possibility of regulations becoming stricter. According to the survey results it appears that for the two Road Administration professionals, the possibility of increased haul distances is the most important benefit accompanied by the WMA methods, followed by the environmental benefits, which they do suspect to become more important in the future.

The respondents were divided about the question of which method would be most likely to be chosen in Iceland. People said either WAM Foam or zeolite/wax; no one said only zeolite or only wax. If looked at who said what, of those that are mostly familiar with the research project with zeolite and wax that is being conducted in Iceland, two said zeolite/wax and two did not give a definite answer. All others were split on the question. There can not be seen any trend of answers between professional sectors, except for that the two producers both said zeolite/wax. The strongest reasoning for choosing WAM Foam was because it is being tested and used in Norway and foaming has been used in Iceland for base stabilization. No two respondents used the same reasoning for choosing zeolite/wax.

According to the answers about where in country WMA would be suitable, it is most likely that WMA would start by being tested and monitored in Reykjavik and then, if used further, be used across the whole country. Interestingly no one used the reduced pollution as a reason for rather using it in the greater Reykjavik area but a contractor mentioned using it for paving in tunnels to reduce workers exposure to emissions.

Answers regarding the suitable type of project for WMA were various and many ideas came up. Examining the answers from the professionals from the Road Administration particularly versus the other ones gives the idea that WMA would be used for medium trafficked roads in and around densely populated areas around the country, often during cold conditions (fall and spring) and possibly also as a stabilizing base course for the highway system.

According to the answers to how much WMA can cost, it will only be an option if it costs the same as or less than regular HMA, unless authorities make regulations stricter, it will improve quality, allow colder weather paving or increase haul distances. If so, the increase in cost can be moderate. An increase in cost was also mentioned by almost half of the respondents as a main drawback.

Half of the respondents said that equipment modifications would not decrease WMA's potential for implementation. Most of the others indicated that it would depend on the cost of the modifications. Both of the professionals from the Road Administration said that the equipment modifications would not decrease interest, and one of the producers said that minor changes are not an obstacle but the other producer said that equipment modifications might prevent implementation. The producers are seemingly a bit more negative, at least towards extensive equipment modifications and that could affect considerations for the WAM Foam method since it includes the most modifications of the three methods.

The answers about whether Iceland would benefit from WMA were split in two; 6 out of 10 said yes, 2 were more cautious but fairly positive and 2 were doubtful. Those four all added that it would only be beneficial if the same/better quality can be reached as for regular HMA. The two more doubtful also said only if it does not cost more. Only two specifically talked about environmental awareness and they had a different view on it. A professional from the Road Administration said that requirements for environmental issues can become more significant in the future and therefore WMA can be beneficial, and a contractor said that environmental awareness is not dominant enough in the paving industry in Iceland today for WMA to be accepted.

The majority of the respondents, 7 out of 10, were positive regarding WMA, one was neutral and two were somewhat negative. Those two, a researcher and a contractor, were mainly negative towards Icelandic conditions and the paving industry's receptivity rather than towards WMA directly. It can be interpreted such that they think WMA can be beneficial in some way but special Icelandic conditions might cause it to be exploited in a different way than in other countries and business incentives are not in place to encourage its adoption.

Examining the answers to these two questions together, i.e. whether WMA can be beneficial for Iceland and what people's general opinion on WMA is, gives a good idea about the respondent's overall opinion towards WMA for cold weather conditions. Five respondents gave positive answers to both questions, three were fairly positive given that certain conditions are met, and two were skeptical. The five positive respondents were a consultant, a producer, both of the professionals from the Road Administration, and a teacher. The three fairly positive respondents were an additives importer, a producer and a consultant. The two skeptical respondents were a researcher and a contractor. The fact that 5 out of the 10 respondents are positive is promising for WMA, and also that thereof are both of the professionals from the Road Administration.

4.3.3.1 Summary of Survey Discussion

To summarize even further, the general conclusions drawn from the survey are:

- Most of the respondents were slightly or fairly familiar with WMA;
- weather conditions cause the most common and most costly paving problems;
- studded tire wear is the most limiting factor for durability;
- energy consumption reduction is the main benefit of WMA;
- energy consumption reduction or emissions reduction alone are not enough incentives but may become one in the future;
- increased haul distances appears to be a more important benefit than reduced emissions;
- good compactability is critical for acceptable pavement performance in Iceland;
- people are cautious because of lack of information about long-term performance;
- WMA could have a significant impact on some key problem areas in Icelandic paving, primarily haul distances;
- people are divided about which method would be suitable for Iceland. Most of those familiar with the Icelandic zeolite/wax research find those methods to be

promising. Those that choose WAM Foam do so primarily because it has been tested in Norway or because foaming has been done in Iceland;

- WMA would start by being tested and monitored in Reykjavik and then, if used further, be used across the whole country;
- if it will be used in Iceland then most likely for medium traffic roads in and around densely populated areas around the country, often during cold conditions (fall and spring) and possibly also as a stabilizing base course for the highway system;
- WMA will only be an option if it costs the same or less, unless there are additional incentives, then it can cost moderately more;
- equipment modifications do not decrease WMA's potential for implementation;
- 5 are positive towards WMA both generally and as an option for Iceland, 3 are fairly positive given that certain conditions are met, and 2 are skeptical about WMA's potential;
- those who are positive are a consultant, a producer, both of the professionals from the Road Administration and a teacher, those fairly positive are an additives importer, a producer and a consultant and those skeptical are a researcher and a contractor.

4.4 Discussion

4.4.1 Warm Mix Asphalt's Advantages and Disadvantages

According to the information that has been gathered about WMA, the following conclusion is drawn about what its advantages and disadvantages are compared to regular HMA.

The primary advantage of WMA over regular HMA is the reduced energy consumption. The emissions reduction is also an important advantage but how beneficial it really is in practice for asphalt producers and buyers is entirely dependent on environmental awareness and regulations in each country. Within each country, reduced emissions are especially beneficial for paving projects in densely populated areas and for non-open air paving. The decreased viscosity of warm mixes is another important benefit.

It makes handling of the mix easier and allows effective compaction at lower temperatures where cool down rates are not as rapid. WMA's disadvantages seem to be mainly related to rutting resistance and moisture susceptibility issues, but it varies depending on each WMA method and may be mitigated with the use of anti-stripping agents. By using WMA processes with regular HMA production temperatures; 1) the temperature gap between production and cessation can be increased, allowing increased haul distances and more time available for compaction during cold weather paving and 2) compaction can be made easier, which can be beneficial for the use of stiff mixes and RAP, paving during extreme weather conditions and reduction in amount of roller compaction.

As was noted previously, both the effect on viscosity and the various application potentials achieved by producing WMA at regular HMA temperatures, can be stated with more confidence for the Sasobit wax method than the other two because the available information about these issues is more extensive for Sasobit. These additional application possibilities have been most obviously marketed for Sasobit wax and least for WAM Foam, whose marketing has entirely focused on the environmental benefits. But of the three methods, least is known about Sasobit wax regarding environmental benefits since very little information was found about environmental issues for it.

Sasobit and WAM Foam give satisfactory rutting resistance results but results for Aspha-min indicate that it may not negate the increased rutting susceptibility, resulting from the lower temperatures, as well as the other two methods. Generally, the lower temperatures used for WMA can result in incomplete drying of the aggregates and the resulting trapped water in the coated aggregates may cause moisture damage. There are indications that anti-stripping agents may be needed in some situations for both Aspha-min zeolite and Sasobit wax for them to result in acceptable performance in terms of moisture susceptibility and they can also increase the rutting resistance. Unfortunately, there is lack of published information about moisture susceptibility for WAM Foam.

4.4.2 Cold Weather Paving

When it comes to cold weather paving considerations, important factors to consider are compactability, moisture susceptibility and binder grade. Compactability is indeed well accounted for by the warm mix methods, since they all reduce the viscosity of the asphalt and have the capability of increasing compaction and thereby reducing permeability.

The conclusion drawn from the available information about WMA's performance in relation to cold weather conditions is that WMA is a viable option for cold weather paving. This can be said about all of the three methods, although there are slight differences in some of their measured performances. However, anti-stripping agents may be needed to decrease rutting and moisture susceptibility. Indeed, many of the advantages gained when WMA is produced at regular HMA temperatures are particularly beneficial for cold weather conditions, e.g. extended paving season, easier compaction during extreme weather conditions and easier compaction for stiff mixes.

4.4.3 Warm Mix Asphalt in Iceland

4.4.3.1 General

In general, the results from the survey can only be interpreted as such that professionals in the paving industry in Iceland are generally positive towards WMA, interested in testing it further for Icelandic conditions, and hopeful about its potential for helping with some key problem areas in paving in Iceland.

The conclusion drawn from the information about WMA's advantages and disadvantages, its suitability for cold weather conditions, general information about Iceland and the results from the survey, is that WMA is a viable option for the paving industry in Iceland.

4.4.3.2 Application Field

According to the survey results, the answer to where in Iceland and for what sort of projects WMA would be most suitable is that it would start by being tested and monitored in and around Reykjavik and then, if used further, be used across the country. Most likely for medium traffic roads in and around densely populated areas, often during cold conditions (fall and spring) and possibly also as a stabilizing base course for the highway system. This result implies that it would be used more for special projects than on a regular basis, i.e. during cold weather and when long haul distances are necessary.

4.4.3.3 Warm Mix Asphalt Method

Although there are various WMA methods available, only the three most prominent in literature were evaluated in this paper. In the survey, people were divided about which of the three methods would be most likely for implementation in Iceland, four said zeolite/wax and three said WAM Foam. In order to evaluate which method is most likely to be considered in Iceland a few factors need to be examined.

First of all, cost is important, and the survey confirmed that. For the Icelandic market, the Aspha-min zeolite is the most costly method according to the cost calculations in chapter 4.2.3. There are indications that the zeolite method does not perform as well as the other two methods regarding rutting and preliminary results from the WMA research in Iceland indicated lesser results for the zeolite than for the wax. On these grounds, it is concluded that the Aspha-min zeolite is least likely of the three methods to be suitable for Icelandic conditions. Cost wise, the WAM Foam and Sasobit methods are based on different ideas. WAM Foam has a high initial cost and a fixed cost per year. Sasobit on the other hand has only a variable cost. WAM Foam therefore requires a certain amount of usage (which for the small Icelandic paving market is a relatively large amount) to pay off the fixed costs, i.e. it requires a certain amount of commitment. Sasobit is therefore more flexible for initial advances and testing (which have started already) which consequently makes it a more likely candidate for future use. Also, as previously noted, the available information about the application potentials when using regular HMA production temperatures is more extensive for Sasobit and more independent research has been conducted on it than on WAM Foam. For example, the possibility of using WAM Foam to increase haul distances has not been examined by the developers. Based on these speculations, it is concluded that the Sasobit wax is most likely of the three methods to be used in Iceland.

A result from the survey regarding cost is that WMA will only be an option if it costs the same or less, unless there are additional incentives, then it can cost moderately more. Sasobit increases the overall production cost by about 2%. If it is used for a production at regular HMA temperatures it increases the cost by about 4%. A 2% increase in cost is very moderate, but are there enough incentives? A 4% increase in cost is also moderate, and in that case there are the various incentives of easier compaction and increased temperature gap. According to the survey, increased haul distances is a very important benefit, even more important than reduced emissions, and therefore it is probably an important enough incentive to accept a 4% increase in production cost.

The reduced energy consumption is the main benefit of WMA according to the survey, but the reduction is not enough to cover the additional cost of Sasobit. Increased haul distances is the second most important benefit according to the survey, important enough to justify a moderate increase in cost. Reduced emissions is the third most important benefit according to the survey but pollution from asphalt plants in Iceland today is within limit boundaries set by authorities, but then again some pollution limits in Iceland are starting to get stricter and it is timely for producers to start seeking ways to reduce emissions. The conclusion drawn from this is therefore that WMA is a promising option for the paving industry in Iceland, Sasobit would be most suitable of the three methods, and the incentives for its usage are twofold: 1) As a compaction aid for mixes produced at, or close to, regular HMA production temperatures, used to increase haul distances and/or pave during cold and difficult weather conditions, and sometimes slightly reduce fuel consumptions as well (a combination that can depend on circumstances each time). 2) As an environmentally friendly method when emissions start to get close to limits, which is not an issue for asphalt producers today but may become an issue in the future with stricter regulations and/or increased production.

5. CONCLUSIONS

The final conclusions of the paper can be categorized into four major conclusions.

1. The primary advantages of warm mix asphalt are; reduced energy consumption, reduced emissions and reduced viscosity at working temperatures.

   The emissions reduction is an important advantage but how beneficial it really is in practice for asphalt producers and buyers is entirely dependent on environmental awareness and regulations in each country. Within each country, reduced emissions are especially beneficial for paving projects in densely populated areas and for non-open air paving. The decreased viscosity of warm mixes is another important benefit. It makes handling of the mix easier and allows effective compaction at lower temperatures where cool down rates are not as rapid. Warm mix asphalt's disadvantages seem to be mainly related to rutting resistance and moisture susceptibility issues, but it varies depending on each warm mix asphalt method and may be mitigated with the use of anti-stripping agents. By using warm mix asphalt processes with regular hot mix asphalt production temperatures; 1) the temperature gap between production and cessation can be increased, allowing increased haul distances and more time available for compaction during cold weather paving and 2) compaction can be made easier, which can be beneficial for the use of stiff mixes and RAP, paving during extreme weather conditions and reduction in amount of roller compaction.

2. Warm mix asphalt is a viable option for cold weather paving.

   The conclusion drawn from the available information about warm mix asphalt's performance in relation to cold weather conditions is that warm mix asphalt is a viable option for cold weather paving. This can be said about all of the three methods, although there are slight differences in some of their measured performances. However, anti-stripping agents may be needed to decrease rutting and moisture susceptibility. Indeed, many of the advantages gained when warm mix asphalt is produced at regular hot mix asphalt temperatures are particularly beneficial for cold weather conditions, e.g. extended paving season, easier compaction during extreme weather conditions and easier compaction for stiff mixes.

3. Warm mix asphalt is a viable option for the paving industry in Iceland.

The conclusion drawn from the information about warm mix asphalt's advantages and disadvantages, its suitability for cold weather conditions, general information about Iceland and the results from the survey, is that warm mix asphalt is a viable option for the paving industry in Iceland.

In general, the results from the survey can only be interpreted as such that professionals in the paving industry in Iceland are generally positive towards warm mix asphalt, interested in testing it further for Icelandic conditions, and hopeful about its potential for helping with some key problem areas in paving in Iceland.

The reduced energy consumption is the main benefit of WMA according to the survey, but the reduction is not enough to cover the additional cost of WMA additives. Increased haul distances is the second most important benefit according to the survey, important enough to justify a moderate increase in cost. Reduced emissions is the third most important benefit according to the survey but pollution from asphalt plants in Iceland today is within limit boundaries set by authorities, but then again some pollution limits in Iceland are starting to get stricter and it is timely for producers to start seeking ways to reduce emissions. The conclusion drawn from this is therefore that warm mix asphalt is a promising option for the paving industry in Iceland and the incentives for its usage are twofold: 1) As a compaction aid for mixes produced at, or close to, regular hot mix asphalt production temperatures, used to increase haul distances and/or pave during cold and difficult weather conditions, and sometimes slightly reduce fuel consumptions as well (a combination that can depend on circumstances each time). 2) As an environmentally friendly method when emissions start to get close to limits, which is not an issue for asphalt producers today but may become an issue in the future with stricter regulations and/or increased production.

According to the survey results, the answer to where in Iceland and for what sort of projects warm mix asphalt would be most suitable is that it would start by being tested and monitored in and around Reykjavik and then, if used further, be used across the country. Most likely for medium trafficked roads in and around densely populated areas, often during cold conditions (fall and spring) and possibly also as a stabilizing base course for the highway system. This result implies that it would be used more for special projects than on a regular basis, i.e. during cold weather and when long haul distances are necessary.

4. Sasobit wax is the most likely method for future use in Iceland.

Of the three methods that were examined in this paper, WAM Foam, Aspha-min zeolite and Sasobit wax, the Aspha-min zeolite method is least likely to be suitable for Icelandic conditions. Sasobit is more flexible than WAM Foam for initial advances and testing which consequently makes it a more likely candidate for future use. Available information about the application potentials when using regular hot mix asphalt production temperatures is more extensive for Sasobit and more independent research has been conducted on it than on WAM Foam. It is therefore concluded that the Sasobit wax is most likely of the three methods to be used in Iceland.

More research is needed for all the warm mix asphalt methods to evaluate both laboratory and field performance more precisely. Warm mix asphalt is a new technology and despite previous laboratory research, long-term performance and how warm mix asphalt affects pavement life will not be fully known until after a few more years. Also, more independent research is needed for all the methods, although especially for WAM Foam, so that potential users can be sure they have unbiased results to base their decisions on.

In Iceland, continuing research on warm mix properties when used with Icelandic aggregates is necessary. In addition to what is already being tested in Iceland it would be especially interesting to examine strength gain and aging and try to evaluate durability, for different methods and mixture and temperature combinations. Also, as results from the survey suggested, test sections made with different methods and various mixture and temperature combinations need to be placed and monitored. Test production and placement with warm mix asphalt processes at regular hot mix asphalt temperatures would also be interesting in order to evaluate the various possibilities warm mix asphalt has to offer as a compaction aid.

The warm mix asphalt methods discussed here are continuously being examined and existing test sections being monitored and newer warm mix asphalt methods are also being developed further. Therefore, new information can continually be expected to arise in coming years and it is important keep track of new inventions.

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APPENDIX A: POLLUTION LIMITS

Pollution limits for a few pollutants according to Icelandic regulation nr. 251/2002; environmental limits and alarm limits.

Environmental limit for particulate matter (PM_{10}):

Environmental Limit	Reference Time	Limit [µg/m^3]	Nr. of times limits may be exceeded in a year	Confidence limits % (µg/m^3)	Valid from
Health protection limit	24 hours	50	35	50% (75)	Valid. of regul.
Health protection limit Guideline value	24 hours	50	7	0% (50)	Valid. of regul.
Health protection limit	24 hours	50	35	37.5% (69)	1.1.2002
Health protection limit	24 hours	50	35	25% (63)	1.1.2003
Health protection limit	24 hours	50	35	12.5% (56)	1.1.2004
Health protection limit	24 hours	50	35	0% (50)	1.1.2005
Health protection limit	24 hours	50	29	0% (50)	1.1.2006
Health protection limit	24 hours	50	23	0% (50)	1.1.2007
Health protection limit	24 hours	50	18	0% (50)	1.1.2008
Health protection limit	24 hours	50	12	0% (50)	1.1.2009
Health protection limit	24 hours	50	7	0% (50)	1.1.2010
Health protection limit	Year	40	-	0% (40)	Valid. of regul.
Health protection limit Guideline value	Year	20	-	0% (20)	Valid. of regul.
Health protection limit	Year	40	-	0% (40)	1.1.2002
Health protection limit	Year	35	-	0% (35)	1.1.2003
Health protection limit	Year	30	-	0% (30)	1.1.2004
Health protection limit	Year	20	-	50% (30)	1.1.2005
Health protection limit	Year	20	-	40% (28)	1.1.2006
Health protection limit	Year	20	-	30% (26)	1.1.2007
Health protection limit	Year	20	-	20% (24)	1.1.2008
Health protection limit	Year	20	-	10% (22)	1.1.2009
Health protection limit	Year	20	-	0% (20)	1.1.2010

* Confidence limits are limits that are set in areas where pollution exceeds environmental limits. Confidence limits specify how much and for how long the environmental limits may be exceeded.

Environmental limit for benzene (C_6H_6):

Environmental Limit	Reference Time	Limit [µg/m^3]	% (µg/m^3)	Valid from
Health protection limit	Year	5	100% (10)	Validation of regulation
Health protection limit	Year	5	80% (9)	1.1.2006
Health protection limit	Year	5	60% (8)	1.1.2007
Health protection limit	Year	5	40% (7)	1.1.2008
Health protection limit	Year	5	20% (6)	1.1.2009
Health protection limit	Year	5	0% (5)	1.1.2010

Environmental limit for nitrogen dioxides (NO_2) and nitrogen oxides (NO_x):

Environmental Limit	Reference Time	Limit [µg/m³]	Nr. of times limits may be exceeded in a year
Health protection limit nitrogen dioxide	1 hour	200	18
Health protection limit nitrogen dioxide	1 hour	110	175
Health protection limit nitrogen dioxide	24 hours	75	7
Health protection limit nitrogen dioxide	Year and winter	30	-
Vegetation protection limit nitrogen oxide	Year	30	-

Nitrogen oxide (NO_x) is the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) calculated as parts of a billion and showed as nitrogen dioxide (NO_2) in $\mu g/m^3$.

Alarm limit for nitrogen dioxides (NO_2):
400 $\mu g/m^3$ measured in 3 consecutive hours at places that describe air quality in at least 100 km^2 or in a whole region or an urban area, whichever is less.

Environmental limit for carbon monoxide (CO):

Environmental Limit	Reference Time	Limit [µg/m³]	Nr. of times limits may be exceeded in a year	Valid from
1. Health protection limit	Max. of daily 8-hour running averages	10		Validation of regulation
2. Health protection limit	8-hour average	6	21	Validation of regulation
3. Health protection limit	1-hour average	20	175	Validation of regulation

APPENDIX B: SURVEY DOCUMENTS

The two documents that were sent to the respondents:

1. A summary of WMA.
2. A questionnaire.

WARM MIX ASPHALT – A SUMMARY

Environmental awareness has been increasing rapidly over the past years and stricter emissions regulations have led to a development in Europe of several new processes to reduce the mixing and compaction temperatures of hot mix asphalt, without sacrificing the quality of the resulting pavement.

Traditional hot mix asphalt is usually produced at temperatures between 140 and 180°C and compacted at about 100 to 150°C. The goal of the warm mix asphalt process is to reduce those high production and compaction temperatures. Its primary benefits are reduction in energy consumption required to heat hot mix asphalt to temperatures above 150°C at the production plant, and reduced emissions from burning fuels, fumes, and odors generated at the plant and the paving site. There are mainly three warm mix asphalt technologies that have been tested and produced:

- A two-component binder system called WAM-Foam (Warm Asphalt Mix Foam).
- The addition of a synthetic zeolite called Aspha-Min during mixing at the plant to create a foaming effect in the binder.
- The use of organic additives such as Sasobit, a Fischer-Tropsch paraffin wax and Asphaltan B, a low molecular weight esterified wax.

All three technologies appear to allow the production of WMA by reducing the viscosity of the asphalt binder at a given temperature. This reduced viscosity allows the aggregate to be fully coated at a lower temperature than what is traditionally required in HMA production.[1]

In the **WAM Foam** process, two different bitumen grades, a soft bitumen grade and a hard bitumen grade, are combined with the mineral aggregate in the asphalt production process. This way, the asphalt mixture can be produced between 100 and 120°C and compacted at 80-90°C.[2] The hard component is added in the form of foam. A WAM Foam modified asphalt plant mixes the soft bitumen first with the mineral aggregate in order to achieve pre-coating. In the second step the foamed bitumen is introduced.[3]

Foamed bitumen is produced by injecting water at a level between 1 and 5% into hot bitumen. The steam produces a large volume of foam that slowly collapses with time.[4]

In a batch asphalt mixing plant the water is injected into the bitumen pipe in a special nozzle system, just before the bitumen enters the mixer. An airgun is used to blow the foaming chamber and pipes clean after each foam injection. Since 1999, several road trials have been carried out in Norway, the Netherlands and the UK. Generally, condition monitoring after placement has revealed very similar results for the warm mix sections as

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[1] Homepage of FHWA; http://www.fhwa.dot.gov/pavement/asphalt/wma.cfm, entered 11.06.05.

[2] Koenders, BG, Stoker, DA, Bowen, C, de Groot, P, Larsen, O, Hardy, D, Wilms, KP. *Innovative processes in asphalt production and application to obtain lower operating temperatures*. 2nd Eurasphalt & Eurobitume Congress, Barcelona, Spain, September 2000.

[3] O.R. Larsen, Ø. Moen, C. Robertus, B.G. Koenders. *WAM Foam asphalt production at lower operating temperatures as an environmental friendly alternative to HMA*. 3rd Eurasphalt & Eurobitume Congress, Vienna, 2004.

[4] B.G. Koenders, D.A. Stoker, C. Robertus, O. Larsen, J. Johansen. *WAM-Foam, Asphalt Production at Lower Operating Temperatures.* International Society for Asphalt Pavements, 9th conference, Copenhagen, 2002.

for comparison hot mix sections. In 2001, productions of WAM Foam in a batch plant and a drum plant were started in Norway for normal (commercial) paving works.[3]

Measurements show that fume emissions during warm mixture production are negligible compared to the emissions during hot mixture production.[5] A measurement from a drum plant in Norway shows that the WAM Foam production resulted in a 40% reduction in diesel consumption, a 31% reduction in CO_2 emissions, a 29% reduction in CO emissions and a 62% reduction in NO_x emissions compared to the hot mix (at identical production rates).[3]

Aspha-min zeolite is a product of Eurovia, and it is a crystalline hydrated aluminum silicate. It contains approximately 21% water by weight and when it is added to the mix at the same time as the binder, the steam creates a volume expansion of the binder. This creates asphalt foam and allows increased workability and aggregate coating at lower temperatures. Eurovia recommends adding aspha-min at a rate of 0.3% by mass to the mix, which enables approximately 30°C reduction in production and laying temperatures.[6,7]

Eurovia states that all known bitumen, polymer modified bitumen and recycled asphalt (RAP) can be used in this process. Also, all normal mineral aggregates and fillers can be used and therefore no modifications to a normal mix design process are needed. The addition into the mixing process is done through special devices with a similar procedure as adding certain types of fibers. The addition of zeolite does not prolong the mixing process. Eurovia states that after the three years that have passed since the first applications of test sections with zeolite, no significant changes have been found in surface characteristics and that the zeolite sections are comparable to hot mix asphalt comparison sections.[8]

The National Center for Asphalt Technology (NCAT) in USA conducted a laboratory study which indicated that the zeolite improves compaction and does not significantly affect resilient modulus or rutting. No evidence support the need for a cure time before traffic can be let on asphalt mixture with zeolite. But in order to get acceptable performance in terms of cohesion and moisture resistance and a decrease in the rutting rate, 1.5% hydrated lime was added. In a field demonstration project the zeolite was introduced into the plant using a specially built feeder. More workability was observed for the warm mix than the control mix. Equal densities were obtained and no signs of distress were noticeable one year after construction.

The zeolite can be added directly into the pugmill in a batch plant, through the RAP collar, or pneumatically fed into a drum plant using a specially built feeder that controls the addition rate.[7]

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[5] P.C. de Groot, C. Bowen, B.G. Koenders, D.A. Stoker, O. Larsen, J. Johansen. *A comparison of emissions from hot mixture and warm asphalt mixture production.* IRF World Meeting, Paris, 2001.

[6] Homepage of Eurovia; http://www.asphamin.com/, entered 11.23.05.

[7] G.C. Hurley and B.D. Prowell. *Evaluation of Aspha-min zeolite for use in warm mix asphalt*. National Center for Asphalt Technology, Auburn University, June 2005.

[8] W. Barthel, J.P. Marchand, M. Von Devivere. *Warm asphalt mixes by adding a synthetic zeolite*. www.asphamin.com, entered 11.03.05.

Measurements conducted for Eurovia indicated a 30% reduction in energy consumption because of a 30-35°C reduction in mix temperature and a 75% reduction in fume emissions resulting from a 26°C reduction in production temperature. Measurements at the application site indicate over 90% reduction in fume emissions when the mix temperature was reduced from 175°C to 140°C and in all cases when zeolite has been added and temperatures reduced, odor has reduced and crew members have confirmed improved working conditions.[8]

Sasobit is a product of Sasol Wax International and it is a mixture of long chain hydrocarbons produced from coal gasification using the Fischer-Tropsch synthesis. Sasol Wax states that Sasobit makes it possible to upgrade softer grades of asphalt to harder grades while at the same time working to overcome deformation and bleeding at high performance temperatures. Sasobits melting point is at about 100°C and it is completely soluble in bitumen at temperatures above 120°C. The reduction in viscosity at working temperatures makes the asphalt easier to process, provides the option of reducing working and mixing temperatures and thereby reducing fume emissions, saving energy and reducing production cycle times. Sasol Wax states that the optimum addition of Sasobit is 3% by weight.[9]

Sasobit's ability to lower the viscosity of the asphalt binder, during both the asphalt mixing process and laying, allows working temperatures to be decreased by 18-54°C. Below its melting point it forms a crystalline network structure that leads to added stability. In Europe, South Africa and Asia, the wax has been added directly to the aggregate mix as pellets or as molten liquid via a dosing meter. In the US, Sasobit has been blended with the binder at the terminal and blown directly into the mixing chamber at the same point as fibers were being added to a stone matrix asphalt (SMA) mix.

NCAT conducted a laboratory study which indicated that Sasobit lowered the measures air voids, improved the compactability at temperatures as low as 88°C, improved rutting rate and did not affect resilient modulus. Sasobit reduced aging of the binder and mixes containing Sasobit were less sensitive, in terms of rutting, to the decreased production temperatures. Additionally, there appears to be no need for any additional cure time before traffic can be let on asphalt mixture with Sasobit. The lower compaction temperature, however, may increase the potential for moisture damage because of incomplete drying of the aggregate.[10]

Over 140 road projects and trials have been constructed using Sasobit, most of them in Germany. The aggregate types used have been various dense graded mixes, stone matrix asphalt (SMA) and gussasphalt.[11]

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[9] Homepage of Sasol Wax; http://www.sasolwax.com, entered 11.29.05.
[10] G.C. Hurley and B.D. Prowell. *Evaluation of Sasobit for use in warm mix asphalt*. National Center for Asphalt Technology, Auburn University, June 2005.
[11] *Roads and trials with Sasobit*.
http://www.sasolwax.com/data/sasolwax_/Bitumen%20Modification/Roads%20and%20trials%20e.pdf, entered 11.29.05.

WARM MIX ASPHALT – A SURVEY

1. What do you think are the most common problems that arise during paving in Iceland?

2. Which of these problems do you think are the most costly ones?

3. What do you think are the most limiting factors for quality and durability of pavements in Iceland (for example regarding mix quality, distress, environmental factors)?

4. How familiar were you with warm mix asphalt before you read the attached summary?
a) Never heard of it before
b) Very little
c) Fairly much
d) Very much

5. What do you think are the main benefits of warm mix asphalt?

6. What do you think are the main drawbacks of warm mix asphalt?

7. Do you think the paving industry in Iceland will benefit from using warm mix asphalt? If so, in what way mainly?

8. If WMA would be produced in Iceland, which of the methods that are mentioned in the following summary (foam, zeolite, wax), do you think would be most likely to be chosen? Why?

9. If warm mix asphalt would be used in Iceland, where in the country (for example, greater Reykjavík area or rural areas, north or south part of the country) do you think it would be most suitable?

10. If warm mix asphalt would be used in Iceland, for what type of projects (for example concerning traffic load, population density, time of year) do you think it would be most suitable?

11. How much do you think a difference in cost between warm mix asphalt and traditional hot mix asphalt matters for WMA's potential in Iceland? In other words, do you think it will be considered an option only if it costs less or as much or could it also be an option if it costs more?

12. Do you think that the equipment modifications that need to be done to produce WMA will decrease its potential for implementation?

13. Do you think this lower mixture temperature will significantly affect factors like the length of the paving season, material transport from the plant to the site and the time from paving until traffic is allowed on the road? How much do you think factors like these matter when choosing paving methods in Iceland?

14. Do you know if there is anything being done in the paving industry in Iceland today that is similar to these warm mix asphalt processes in some way?

15. What do you think would be the next steps in investigating the potential for implementation of warm mix asphalt in Iceland?

16. What is your general opinion so far on warm mix asphalt?

17. Is there anything else that you would like to mention?

APPENDIX C: SURVEY RESULTS

Answers to the questionnaire from all the participants. Note that the survey was conducted in Icelandic and these are therefore translated versions. The translation was done as directly as possible so that no information would be forfeited.

1. What do you think are the most common problems that arise during paving in Iceland?

- Given that the question is about the production and placement processes, I think it is a) moisture in the aggregates because of porosity, b) lack of aggregates with well defined gradation (within stringent boundaries), c) lack of aggregates with good toughness and abrasion resistance (a, b and c have been improved in the last years by importing aggregates), d) temperature differentials resulting from placement of a cooler portion of HMA mass into the mat which do not compact well enough and cause damage later on, e) defective and outdated asphalt plants at some locations, and f) cold and wet weather.

- The biggest problems in paving are primarily because of lack of groundwork and weather conditions, placement is done in rain and too much cold. Regarding the material itself, i.e. the asphalt, it is probably if it cools too much before placement and becomes too viscous and does not compact well enough.

- Primarily weather conditions and not enough good aggregates.

- Primarily weather conditions. At some places in the country there can be difficulties in providing aggregates that fulfill quality requirements, especially fines.

- The most common problem with the process is changeable weather, lack of good aggregates and the thin population, i.e. few plants and too long haul distances.

- The most common problems are related to weather conditions, i.e. problems related to drying of aggregates during production in rain and cooling during placement that affects the quality of work. Also, aggregate segregation.

- Low air temperature, rain, wind, haul distances, i.e. everything that contributes to cooling.

- From the Road Administration's viewpoint, which would like to use hot mix asphalt more widely around the country, the haul distances are the largest problem. Cost wise, surface dressing is always a better option than HMA. Wear because of studded tires is a cause for pavement maintenance in Iceland.

- Weather conditions, i.e. changeable weather and low temperature. Relatively short paving season which causes short-term recruitment of workers.

- In Iceland, paving is often done during difficult weather conditions and during transport and placement the material cools down and workers experience temperature differentials, transverse screed marks, joints become ugly and handwork can be seen clearly.

2. Which of these problems do you think are the most costly ones?

- I can not answer this question properly. For travelers the damages are worst, but perhaps moisture in the aggregates is a large factor because of drying cost.

- This is rather difficult to evaluate, but it is probably very expensive to throw away material because it has become too cold. Also very expensive to use bad pavement that will not last as many years because of insufficient compaction.

- Few good aggregates.

- The country's orientation is expensive, i.e. the climate and its consequences.

- I have no numbers but can imagine that changeable weather and the short paving season are large factors.

- Problems related to weather.

- Low air temperature.

- Wear because of studded tires cost money but also save lives and save other costs in the society.

- Short paving season and therefore high fixed cost in equipment and workers training.

- Repair of low quality areas in the pavement and a shorter pavement lifetime because of poor quality.

3. What do you think are the most limiting factors for quality and durability of pavements in Iceland (for example regarding mix quality, distress, environmental factors)?

- I think that studded tire wear is the predominant factor (because of the cost of aggregates with good toughness and abrasion resistance). Pavement durability is possibly only about a half or a third of what it could be without studded tire wear.

- For the quality of the mixture and service life of the pavement, aggregate quality, i.e. toughness and abrasion of Icelandic aggregates are not sufficient and aggregates are imported from Norway for use where the heaviest traffic is. The Icelandic climate is also important, i.e. cold and wet weather during placement and many freeze-thaw cycles during the winter, especially in the southwest part of the country. Also, street salting, e.g. in Reykjavik.

- Studded tires.

- Moist climate and studded tires where traffic is heavy. Where wear is not a predominant factor it is probably aging characteristics.

- Aggregate quality, studded tire wear, climate and heavy salt usage. Occasionally, flaw in the pavement or the placement.

- If I look at reasons for replacing pavement, it is clear that: 1) studded tire wear and rutting is a predominant factor for pavement service life. 2) bad practices during placement result in local area damages and if 10-20% of the surface are damaged it is not useable. If I look only at factors that arise during production and placement and affect service life, the problems are: 1) Compaction is the most difficult process in the placement. Weather affects the need for compaction and compaction practices and many problems arise from that. 2) Common Icelandic aggregates are not homogeneous, i.e. they can contain weak and strong or solid and blistery particles. This variability can affect the drying process, amount of binder needed and other factors that affect service life and workability.

- Weather conditions, studded tires, poor aggregate quality.

- Modified binders have been used on very few occasions in Iceland and SBS and EVA modified binders have increased durability but at the same time the job mix formula was changed so it is difficult to see which factor contributed to the increased durability.

- Insufficient aggregate toughness and excessive use of studded tires, especially in urban areas.

- Studded tire wear is the biggest problem. Pavement service life is a lot shorter than for comparable pavement where studded tires are not used.

4. How familiar were you with warm mix asphalt before you read the attached summary?
a) Never heard of it before   b) Very little   c) Fairly much   d) Very much
- b) Very little

- Rather little

- c) Fairly much

- b) Very little

- c) Fairly much. I am familiar with foaming methods but not Sasobit.

- a)

- d) Very much. I have been watching this over the years.

- b) Very little

- c) Fairly much. We had heard of various experiments and are familiar with Sasobit.

5. What do you think are the main benefits of warm mix asphalt?

- Definitely an advantage to be able to produce and lay at a lower temperature than normally. Other things being equal, I think the energy reduction is most important, second is easier compaction (especially for SMA with a hard binder, pen <100 which is rather cumbersome during placement) and thirdly lower emissions. However, the question is if the energy reduction is realistic because the aggregates need to be heated to high temperatures to dry quickly because Icelandic aggregates are usually porous and contain much water, compared to what is common in the other Nordic countries.

- The possibility of placement at a lower temperature. Important when there are long haul distances.

- Reduction in energy consumption and lower emissions.

- Reduction in energy consumption and environmental factors.

- Reduction in heat i.e. energy consumption during production and placement and the possibility of longer haul distances.

- Reduction in energy consumption during production is a factor that will be used to evaluate the benefits of WMA if it will lower the overall cost of a project. If additives cause an increase in the overall cost of a project, WMA does not have a chance on the market. The largest HMA buyers, i.e. the Road Administration and the City of Reykjavik, are not ready to value improved environmental effects of anything. That will not be done until regulations will be set that must be enforced.

- More suitable for Icelandic weather conditions. Allows longer haul distances.

- Hopefully this technology will enable the possibility of paving at locations that are too small to take a portable asphalt plant to and too far away from fixed location plants for safe haul distances. An analysis has been done on shipping a hot mixture but it such a project has not been done even though it is well known e.g. in Faroe Islands and Norway.

- Reduction in energy consumption because of lower temperatures, longer paving season and lower environmental impact of production and placement in urban areas. The last point is more relevant in most other countries than Iceland.

- If the mix will be more workable at lower temperatures it can help with many of the problems mentioned in question 1. However, the question is will the temperature loss remain the same so that people will continue to have the same problems, just at lower temperatures. Would it be possible to continue to produce at high temperatures but increase the time available to finish the paving process? If so, the benefits of reduction in energy consumption and a cleaner production will recede.

6. What do you think are the main drawbacks of warm mix asphalt?

- First, lack of experience with warm mix asphalt, second, usage of additives that incur moisture (the zeolite, foamed bitumen and everything that can actuate absorption in the mix because it might affect the adhesion between the binder and aggregate). Third, increased cost.

- The possibility of incomplete drying of aggregates that causes the water that will be left on the aggregate to freeze during the first winter. Icelandic aggregates are relatively porous and contain much water and lower mixing temperatures may not be sufficient to fully dry them.

- It is questionable whether same quality can be reached and cost can increase, but it will take a few years to find the final answer to that.

- Probably depends on which method would be chosen. Regarding the zeolites it is important to consider the effects of the water that is released during production, considering Icelandic weather conditions.

- Do not know about effects on quality. The need for additives and/or more complicated equipment for the production could be considered a drawback. Drawback if cost increases much.

- Not convinced that foaming methods like the one described in the summary will be comparable to regular HMA, regarding service life, mixture homogeneity, adhesion between binder and aggregates and loss of aggregates from the pavement surface.

- No drawbacks if same quality can be reached.

- Not enough known yet, but excessive praises from developers are a cause for concern. Increased cost seems inevitable but relative when other factors are considered, such as long haul distances, weather conditions and possible environmental impact requirements.

- More difficult mixing and placement procedures than for regular HMA. Lack of experience that might cause initial difficulties.

- Don’t know.

7. Do you think the paving industry in Iceland will benefit from using warm mix asphalt? If so, in what way mainly?

- At present I doubt it. First, there would have to be some experiments conducted to see if WMA will be all right in Icelandic conditions (many freeze-thaw cycles, rainy weather). Second, whether it pays off needs to be checked. Also, soft bitumen (pen 150-200) is used a lot in Iceland and it is quite workable during placement under normal circumstances. But the energy savings is positive, also lower environmental impact, and probably the paving season could be extended but paving late in the fall has worked tolerably as long as the weather stays dry. Then days of fair-weather are used to pave the streets with the heaviest traffic and local streets are paved later in the fall.

- Mostly concerning lower placement temperature.

- The benefit we see now is more efficiency from the portable asphalt plants and probably increased haul distances when working in rural areas.

- Definitely a benefit. Both regarding the energy savings and the environmental issues.

- The benefit are reduced energy consumption, reduced pollution and the possibility of longer haul distances, but that is often a limiting factor in Iceland since there are few asphalt plants.

- I do not believe that the words “environmental awareness” are dominant enough in the paving industry in Iceland today for WMA to be accepted. Especially if there is not a cost reduction and no certainty for at least the same service life.

- Yes, given that the same quality can be reached.

- The benefits are twofold. First, the lower placement temperature offers the possibility of usage in unfavorable external conditions. Second, requirements for environmental issues can become more significant in the future.

- Yes, most likely. Primarily, because of the possible extension of the paving season and also since the method is presumably environmentally friendly. Workers protection might also encourage WMA usage.

- Yes, if it can be showed that it will be possible to reduce quality problems and reduce energy consumption and lower emissions.

8. If WMA would be produced in Iceland, which of the methods that are mentioned in the following summary (foam, zeolite, wax), do you think would be most likely to be chosen? Why?

- My guess is the foamed bitumen, not because it is necessarily the mostly suitable one but because there is some experience with it from base stabilization, and it is more likely that people will use that experience rather than starting something new. However, I can not positively recommend one method above other.

- I do not have enough knowledge to evaluate this.

- I can not answer this now.

- Foam is probably least likely, but my opinion might be affected by the fact that I know the least about that and also because it is patented. Apart from that, research results and cost are predominant factors.

- I can not answer this, but I can say that zeolite and wax methods are being tested and therefore they are likely to be looked at first.

- I do not have enough knowledge to evaluate that. Although, my experience of the market is that the least expensive method always looks best to the buyers. Therefore I think that WAM-Foam would be the first option. It also always looks good to the Road Administration if a method has been tested in the Nordic countries.

- I do not know enough about equipment at the asphalt plants to evaluate this but foam seems to need the most complicated and delicate equipment.

- I can not answer this now but current research is directed at zeolites (Aspha-min) and wax and seems promising. Foam has been used for years for base stabilization with good results.

- Very difficult to evaluate. My guess is WAM-Foam, since Norwegians have tested it and we often go with what they and other Nordic countries do.

- Using additives like zeolite and wax is more likely, water in a pipe to the mixer or into the bitumen is more difficult e.g. because of frost problems.

9. If warm mix asphalt would be used in Iceland, where in the country (for example, greater Reykjavík area or rural areas, north or south part of the country) do you think it would be most suitable?

- Probably in the greater Reykjavik area, elsewhere there is so little traffic that an inexpensive pavement with a soft binder would rather be chosen. WMA could be possible though where there are no asphalt plants within reasonable distance, there it could be an advantage to have the possibility of a pavement that can be placed with acceptable results even if it is relatively cold after a long haul distance (>200 km). That does not occur often, but happens.

- Where the distance from an asphalt plant is relatively long as it commonly is outside of the greater Reykjavik area.

- Outside of the greater Reykjavik area.

- Possibly mostly suitable outside of the greater Reykjavik area, although it is not unlikely to be produced in the greater Reykjavik area since the largest asphalt plants are there. Possible areas are therefore neighboring municipalities, those that are in or close to the service area of the asphalt plants located in the greater Reykjavik area.

- A development of the method would probably start in and around the greater Reykjavik area. The paving industry in Iceland is very small and not many possibilities for development projects outside of that area. If the method will be successful it might be useful in and around places like Isafjordur, Akureyri and Egilsstadir.

- Since WMA requires the same basic equipment as regular HMA production the first usage would be in the greater Reykjavik area. Asphalt plants outside of that area are not capable of being innovators in this field. It could be recommended that this method be used for paving in tunnels to reduce pollution during the placement itself to improve the working environment.

- Everywhere. HMA would then only be used near the asphalt plants during the midsummer.

- At this point it can be expected that towns that are far away from asphalt plants would be chosen. Now there are asphalt plants in Keflavik, Hafnafjordur, Reykjavik, Akureyri, Egilsstadir and Vestmannaeyjar. Everything farther east than Vik is more than a 2 hour drive from Reykjavik and so are towns on Snaefellsnes and the northwest part of the country. Saudarkrokur and Husavik are within reach from Akureyri but other towns in the northeast part of the country are far away. The area south of Breiddalsvik is beyond regular haul distances for HMA apart from the cost of transporting the mix long distances. There exists a portable asphalt plant that has been used e.g. in Isafjordur, but from Isafjordur to Patreksfjordur and Holmavik there is a 2½ to 3 hour drive.

- Probably in the greater Reykjavik area and the south part of the country since pavement innovations are usually tested at these areas first. This is also where the best equipped asphalt plants and most qualified workers are.

- It could be suitable for all asphalt plants in the country.

10. If warm mix asphalt would be used in Iceland, for what type of projects (for example concerning traffic load, population density, time of year) do you think it would be most suitable?

- In my opinion there are two options. First, as a binder for SMA with a hard binder (pen <100) and second, during cold conditions (cold weather and thin lift that cools quickly, placement on a frozen base).

- Use it for less densely populated areas, fall and spring and lower traffic volumes.

- At this point it is not possible to estimate that. A test section needs to be laid first etc.

- Most suitable for average to low traffic volumes outside the largest towns, e.g. on the country's highway system. It could also be suitable in smaller towns. There are indications that the wax may increase the pavement's capacity and therefore it might be an option on wharfs and other locations with heavy loads. The summer is the paving season in Iceland.

- At this point I think the projects would mainly be in densely populated areas, i.e. streets and lots, highways close to towns and airports. The Road Administration uses surface dressing on most highways except where traffic exceeds about 2000 AADT and it does not look like it will change that strategy in the nearest future.

- It is probably best to choose projects where studded tire wear is not a key factor in the pavement's service life. Projects like that could be where there is a lot of truck traffic. Furthermore, WMA could be tested as a base layer where the surface course (regular HMA) is laid one year later.

- Roads/streets with relatively light traffic, spring and fall.

- My hope is that WMA will be used as afréttingarmassi for the highway system and as a maintenance pavement for main roads in towns that are far away from asphalt plants.

- WMA would probably be used for short sections with variable traffic loads for research. The first roads would probably be ones that the Road Administration is responsible for and are outside densely populated areas.

- It could be suitable everywhere except for the roads with the heaviest traffic which are usually paved during the best circumstances. More likely fall and winter to help solve quality issues.

11. How much do you think a difference in cost between warm mix asphalt and traditional hot mix asphalt matters for WMA's potential in Iceland? In other words, do you think it will be considered an option only if it costs less or as much or could it also be an option if it costs more?

- Considering that most pavement projects are successful (at least nowadays), I think that WMA will only be an option if its total cost is lower than for regular HMA.

- It could cost more but not much, maybe 5-10% more.

- Cost is very important for Icelandic road construction and I do not expect the government will set requirements for emissions.

- Unlikely an option if it costs more, unless instructed by authorities. It is an option if it costs the same and especially if it is less expensive.

- WMA can be an option even though it costs more if people decide to put more emphasis on environmental issues than is done today. Also, if it will be possible to pave in colder weather or transport the mix longer distances and make it an option at more locations than today. (We have used surface dressing on residential streets in many towns throughout the country because HMA has not been an option because of distance to an asphalt plant and if the project is too small to pay for portable asphalt plant transfer.)

- Cost is very important. I think WMA is not an option if it costs more unless a longer service life is guaranteed.

- The less expensive the more probability for usage but it may cost more if quality is improved.

- If results will be comparable or better than for paving with regular HMA, a moderate increase in cost will not prevent its usage where it will be considered suitable.

- WMA could most likely not cost more than proven HMA. WMA could become less expensive if mixes with environmental impact (e.g. HMA) would be taxed specifically because of the environmental impact.

- It can be a possibility if it costs more but it is much less likely unless buyers require it.

12. Do you think that the equipment modifications that need to be done to produce WMA will decrease its potential for implementation?

- I do not realize how high the cost is. But I think it is likely to decrease interest, at least until it can be shown that WMA usage pays off.

- It depends on the cost of the modifications.

- Equipment should not be an issue.

- Not sure exactly what modifications need to be done, or what they cost, but minor modifications are not an obstacle.

- No, I do not think that cost is important.

- I'm not necessarily certain that the modifications are very costly. Still I think it is unlikely that anyone will do the modifications unless public funds for experimental projects will pay for it or if an increased market is foreseeable.

- No.

- No.

- I don't know but it depends on whether WMA will be adopted.

- Yes, it can stop the whole thing.

13. Do you think this lower mixture temperature will significantly affect factors like the length of the paving season, material transport from the plant to the site and the time from paving until traffic is allowed on the road? How much do you think factors like these matter when choosing paving methods in Iceland?

- My feeling is that the paving season is not so much dependent on temperature, and asphalt mix has been transported very long distances (Reykjavik-Kirkjubaejarklaustur, Reykjavik-Hvammstangi) and laid with acceptable results to my best knowledge, but then good days are chosen for that. Maybe the time from paving until traffic is allowed has some positive effects for WMA but I do not think that is an important factor.

- Yes

- Lower temperature can affect all these factors, see question nr. 7.

- This mainly affects haul distances and that is important when choosing a method.

- Some of these factors are important and others not. Haul distance from asphalt plant is often important outside of the greater Reykjavik area but less important close to the plants.

- I can not see that WMA will affect these factors. I do though suspect that foamed asphalt is more sensitive to low air temperatures and rain than regular asphalt. I have noticed this during base stabilizing with foamed bitumen.

- Yes. Very much.

- We hope that it will be possible to transport the mixture longer distances with good results. The paving season seems to be unlimited now. The quality of paving during frost is another matter.

- The most influential factor is the length of the paving season. Other factors are less important if WMA's quality is comparable to HMA's quality.

- It might have a profound effect on haul distances, nowadays paving is done all year round in Iceland.

14. Do you know if there is anything being done in the paving industry in Iceland today that is similar to these warm mix asphalt processes in some way?
- Not exactly. But as similar "in some way" base stabilization with foamed asphalt (similar to WAM-Foam) can be mentioned, which has been successful to my best knowledge, but that is produced on site, not in a plant. Bitumen emulsion, which is a cold process, has been tried a bit in surface dressing but the results have not all been good. They have not been tried in asphalt to my knowledge. Also, there is a research going on directed by Sigursteinn Hjartarson from the Road Administration.

- Not to my knowledge.

- Hladbaer-Colas could be doing some work with foamed asphalt but nothing has been reported from them.

- The research that is being done by Hofdi for the Road Administration's Research Fund is the only thing I know of. Hladbaer-Colas is owned by the Danish company Colas and therefore they have ready access to information about what is going on in Europe. They are strengthening their knowledge on bitumen emulsion production, but otherwise I'm not familiar with their research or development projects.

- The Road Administration, Hofdi and Kemis ltd. are working together on a research project that examines asphalt with zeolites from Eurovia and wax from Sasol Wax. So far the research has been conducted in laboratory but will probably end with building a test section.

- For the last few years there has been done some work with cold mixes based on bitumen emulsion. I took part in that work and know how buyers and public agencies respond to innovation.

- No.

- We have a research project going on that was originally supposed to show results of using Aspha-min zeolites and wax was added to the research.

- I am not aware of any experiments being prepared for laying WMA test section. The only thing that could be related to WMA is probably literature search.

- Hofdi was planning on doing a research with some material but we are not familiar with it.

15. What do you think would be the next steps in investigating the potential for implementation of warm mix asphalt in Iceland?
- When the research project mentioned earlier is finished, do a test with mixing and placement and do cost-benefit calculations along with it.

- Look at advantages and disadvantages of the methods, also cost of modifications and if/how easy it is to have plants and equipment that work for current methods and the new one. Take a good look at the difference of other people's experience regarding wear, we have freeze/thaw cycles and studded tires that must be remembered.

- Place a test section.

- Place a test section

- Laboratory research is being conducted and I think that the next step is to place a test section.

- Apply for a grant from the Road Administration and conduct a research along with professionals from the Building Research Institute. Also important to include a willing contractor.

- Place a few test sections under various conditions.

- It depends on the results from the laboratory research, but test sections will probably be placed next summer.

- Apply for a grant from the Road Administration's Research Fund and cooperate with one or more producers. Cooperating with research institutes and universities would not hurt. There is also a possibility that the Road Administration would participate in an international project, preferably Nordic or European, that would examine WMA.

- The next step is to do an experiment and test the materials.

16. What is your general opinion so far on warm mix asphalt?

- Conducting some research on WMA under Icelandic conditions is positive but I am very doubtful about its future considering the way things are here.

- I like it and think it is worth while to do some research with it.

- We are still conducting a research and therefore I have no opinion yet.

- A very interesting option.

- WMA is an interesting option because of environmental issues and especially if it will allow longer haul distances and placement at lower temperatures than before.

- Not bad as such. But it is clear that no one embraces new methods because people know what they have but not what they will get. Those that are in charge of these things in

Iceland are willing to test but not in large steps and even if research results are good people still need to be convinced that a method is desirable etc.

- A very good thing.

- It is promising regarding increased usage of asphalt in rural areas.

- WMA is worth being looked into more, at least watch research and development abroad to start with.

- Interesting to look at for the future.

17. Is there anything else that you would like to mention?

- As you can see I am rather negative towards WMA. I am probably overly conservative. On the other hand I do not know very much about WMA and you should not pay too much attention to what I say.

While I was writing this it came to my mind that we do have some trouble with surface dressings, bleeding tends to occur during heat because the binder is soft and mixed with white spirit. Maybe this could be improved by mixing the binder with wax like is done in the Sasobit method; keep it soft above 60-80°C (140-176°F), but stiffer than regular surface dressing binder below that. If I remember correctly I was once taught that wax is not preferable in asphalt binders because of contraction/thermal cracking during frost. Here there is rarely much frost and the surface dressing binder is soft and perhaps there is not much risk that wax will spoil that sort of a binder. Perhaps it would also be possible to lay surface dressing in a colder weather than otherwise if the binder would be mixed with wax. It does though cool very rapidly after it is sprayed on the road which is not good. But this could be looked into more closely.

It is also interesting to be able to lower emissions during placement. I have heard that workers have complained about SMA modified with EVA (Ethyl-vinyl-acetate) (it was laid on a test section in Reykjavik 10 years ago).

- This process must be worked on slowly but positively because mistakes can ruin good ideas.

- It is likely that the largest pavement buyers, i.e. the City of Reykjavik and the Road Administration, will primarily control whether matters like these develop in Iceland. If these parties will start to put more emphasis on environmental issues or see some other benefits in using WMA, the method will prevail here.

- Considering previous experience with full depth experiments here, I do not expect WMA will be tested here until some experience will be reached abroad. Anything could happen through international cooperation and Hladbaer-Colas is a part of a large multinational company in road construction.