INTERACTION BETWEEN ICELANDIC BASALT AND SWEDISH GRANITE WITH SWEDISH BITUMEN EMULSION

Degree project in Chemical Science and Engineering, second cycle, 30 credits. KTH, Stockholm, Sweden 2018

Björk Úlfarsdóttir

HLAÐBÆR COLAS

Table of Contents

Abstract

Like in any modern civilization, roads in Iceland have an important role in the daily lives of inhabitants. Consequently, road quality is of equal importance, but Icelandic roads have shown problems when surface dressing is used where it looks decent after being paved during summer but then deforming pretty rapidly after being hit by elements of winter. Roads in Sweden however, do not seem to have the same problem.

The aim of this study is to minimize this road deformation by examining surface dressing and aggregates. The Icelandic climate is also a factor to this problem since the humidity is comparatively high, summers are cool, winters are mild and the climate is overall challenging. Furthermore, winter thaws are distinctive characteristic of the Icelandic weather, which increases strain on the asphalt.

An experiment was conducted where the adhesion of surface dressing that is common in Sweden was tested with two different aggregates by Vialit plate shock test method. First it was tested with Swedish granite and then with Icelandic basalt. The results from the aggregates were compared where the adhesion with the granite was stronger than with the basalt.

Previous study have found that by choosing binder and aggregate that have high adhesivity at low temperature reduces the risk of surface dressing defects, especially when paving takes place in the early and late summer season. When choosing aggregates for road construction the main criteria is cost, therefore aggregates that are used usually reflect the local geology because transporting aggregates for significant distances is expensive. Concluding from the experiment, it is not recommended to use the basalt with the Swedish surface dressing in practice now due to the lesser adhesion compared to the granite. However further research on the asphalt mix with the Swedish surface dressing and the basalt should be conducted.

Acknowledgements

First I would like to thank my supervisor Lars J. Petterson for being very helpful throughout this process.

I would also like to thank my employer, Malbikunarstöðin Hlaðbær Colas for allowing me to carry out this project. Especially I would like to thank Sigþór Sigurðsson, Sigurður Benediktsson and Gísli Eymarsson for their passionate participation and input.

I would also like to thank Nynas for the use of materials and equipment. With special thanks to Henrik Arnedal who helped me carry out the experiments and was also a great source of knowledge.

Then I would like to thank Vegagerðin for supporting and partially funding this thesis.

Finally, I would like to thank my family and friends for providing me support and encouragement throughout my years of study. Special thanks to Sólrún for listening to me complaining when something did not work out the way I had hoped. Another special thanks to my Stockholm family that I have gained during my master's, my amazing friends that have been like a family away from home. Thank you for making the last two years memorable and always being a source of help and happiness. Last but not least, I would like to thank my brother, Leifi, for reading and giving me comments on my thesis. Furthermore for always being ready to help whenever he can with his continuous patience for his little sister.

Thank you.

1. Introduction

Ever since the Roman Empire and to this day, roads have been of high significance in terms of transportations. Iceland is no exception and with both increasing local community and growing tourist population the good quality roads is more important than ever before. That being said, when using surface dressing in Iceland there have been problems where the asphalt looks good after being paved during the summer time but is often deformed after facing the elements of winter. Roads in Sweden however, do not deal with this problem in general to the same extent. Where Sweden has found a good combination of emulsion and aggregate and therefore do not have to try the performance of the emulsion and aggregates together. Therefore it is interesting to test how well Icelandic aggregates work with their emulsion, based on those result perhaps it can lead to improved and more sustainable roads for the Icelandic population.

Bitumen emulsion is an interesting option for road construction and is used all over the world. It is economical and environmental possibility to make asphalt because it has less fumes, is possible to recycle and use recycled asphalt with it. Furthermore by using surface dressing, which is a type of bitumen emulsion, it is possible to pave many square meters per day because it cures fast.

In this study surface dressing will be investigated, what bitumen is, how the emulsion is produced, what type of aggregates are wanted for surface dressing and how the emulsion and aggregates adhere together. Furthermore the adhesion between two different aggregates with one type of bitumen emulsion was evaluated with the Vialit plate shock test method. Good adhesion between a binder and aggregate is essential to have good surface dressing. It is important to make sure that in cool conditions the adhesion bond can be acquired but that is when adhesivity problems become major. By choosing binder and aggregate that have high adhesivity at low temperature it reduces the risk of surface

dressing defects, especially when paving takes place in the early and late summer season. [1]

2. Bitumen

The term bitumen has different meanings in different parts of the world. In Canada the term "bitumen" is used for heavy crude oils. The European definition is that bitumen is a residue from certain crude oil distillation but can also be found in nature as "natural asphalt". [2, 3] In North America the term "asphalt" or "asphalt binder" is the synonym for bitumen in Europe. However outside of North America "asphalt" is a term for mixtures of bitumen with mineral materials. [3] In this report the European definition will be used.

Bitumen is often confused with coal derived products i.e. coal tar. The coal tar is produced by high-temperature pyrolysis of bituminous coals and does not have the same composition, physical characteristics or potential health risks as bitumen.[3] Bitumen is black and is a visco-elastic material where it behaves as elastic solid at low temperature however as temperature increases the bitumen gets softer and becomes viscous liquid. [2, 3] Most books and papers about bitumen chemistry say that bitumen is a colloidal dispersion of asphaltenes in maltenes that is stabilized by resins however the true chemical nature of bitumen is not fully known. The theory is based on the fact that when bitumen is diluted with specific hydrocarbon liquids a precipitate is formed that is called "asphaltenes" [2]

It is common to divide bitumen into four broad polar fractions of asphaltenes and maltenes that is separated into three types of molecules: saturates, aromatics and resins, together they are called SARA. [3]
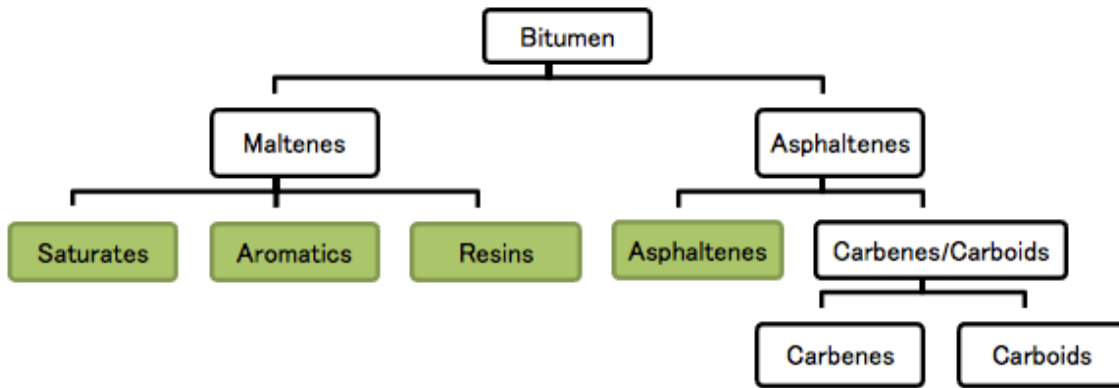
Figure 1: Bitumen substance groups. [4]

SARA composition can be used to predict properties e.g. density, viscosity, boiling temperature and asphaltene stability of the bitumen. [5] Asphaltene is precipitated by n-heptane from the other fractions while the other three are separated by chromatography. [3] Saturates are non-polar branched aliphatic hydrocarbons and straight chains, which is between 5-20% of the bitumen. (e.g. ethane, butane), aromatics are non-polar aliphatic chains and unsaturated rings and is approximately 40-60% of bitumen (e.g. benzene), resins are like a stabilizer for the asphaltenes and are similar to them in chemical composition (e.g. polyurethane). However, asphaltenes are complex, have a very high molecular weight and are composed of mostly carbon and hydrogen with additional nitrogen, sulphur and oxygen. They are amorphous and fairly polar due to unsaturated (C=C) double bond, nitrogen, sulphur and oxygen content. [3, 4, 6] The ratio between resins and asphaltenes imposes the bitumen's physical nature. [6]

It is estimated that approximately 87 Million tons of bitumen is produced in the world per year. Where 85% is used as a binder for asphalt pavements but the remaining 15% is used for roofing and other variety of applications e.g. water pipe coating, waterproofing and sealing materials. Bitumen for road construction can be obtained from crude oil, oil sands and oil shale. It depends on the feedstock used for manufacturing bitumen how its quality and properties will be. Oil sand is a mixture of bitumen, minerals and water. Bitumen can be extracted

from the sand by either cast mining or by in-situ heating. Afterwards it is cleaned to get rid of impurities and then, to transport it easily, it is either hydro processed to make lighter synthetic crude or it is mixed with a light condensate, then the mixture is called dilbit crude oil. Afterwards it is sent to a refinery for distillation and processing. Oil shale is a fine grained rock that holds a substance which is a forerunner of crude oil, called kerogen. It has not been buried deep enough or gotten hot enough to make conventional crude oil and gas. The extraction is similar as for oil sand however to convert it to hydrocarbons it must be heated to high temperature without oxygen. Then it is transported to refineries for conventional processing. [3] Generally crude oil is used to get bitumen.

Crude oil is classified by °API gravity which is a measurement unit from the American Petroleum Institute. It is a scale that uses an index that is related to the oil relative density.[7]

$$°API = \frac{141.5}{d_r(\frac{60}{60})} - 131.5 \qquad (1)$$

Where d_r is relative density with respect to water, at 15.5 °C. [7, 8]

The classification can be seen in Table 1. [8]

Table 1: Crude oil classification by °API gravity. [8]

Oil class	°API
Light	31.1 < °API
Medium	22.3 < °API < 31.1
Heavy	10 <°API ≤ 22.3
Extra-heavy	°API ≤ 10

There are fundamental differences between extra-heavy oil, heavy oil, medium oil and conventional (light) oil. The hydrocarbon fractions: paraffinic, naphthenic and aromatic are different and their volatilities. [9]

To get bitumen from crude oil the first step is to desalt the oil to control bituminous electrical properties and water absorbing tendency. Then the oil is

heated and injected to atmospheric distillation to separate the substances with different boiling points from each other. [3, 10] The ones with the highest boiling points are then sent to vacuum distillation unit. The vacuum is maintained at 10 to 150 mm of mercury, depending on what type of crude oil is being processed. Due to low pressure it is possible to vaporize the heavy oil while avoiding to heat the residuum too much.[10] The vacuum distillation is used to get vacuum residuum that can be used directly as bitumen, processed further or used as a component of blended bitumen. [3] How much consistency the residue has is dependent on the nature of the oil, the rate when it enters the distillation unit, temperature when it enters and goes through the still, pressure in the vacuum and the rate when it leaves the unit.[10]
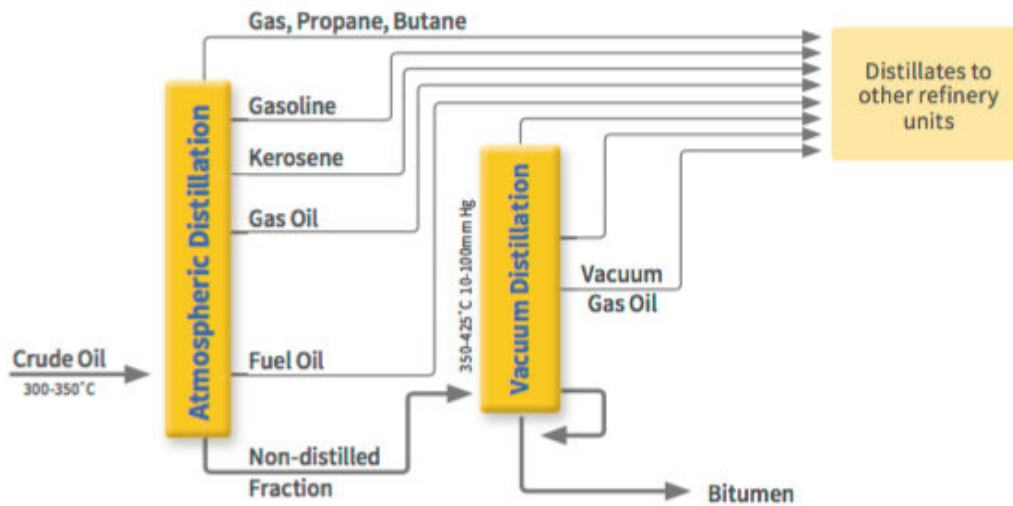

Figure 2: Schematic diagram of the distillation process [3]

Then it is also possible to get bitumen by air blowing operation. [10] Subsequently oxidation is used to change the physical properties of the bitumen by making it harder, this is measured by decrease in penetration, increased viscosity and higher softening point. [3] It causes the bitumen to become harder at high temperatures while partially keeping the soft properties at lower temperatures. [2] This can be done to vacuum residuum and/or bitumen that do not have the correct technical specification even for those that are not possible to use directly in the manufacture of paving bitumen. [3, 10] The process takes

place in a bitumen oxidation unit where a catalyst may be used to make the reaction quicker and enhance temperature vulnerability of the product comparative to oxidation without a catalyst. [3] In the process the aromatic compounds in the feedstock are oxidized with air under controlled condition to make hydrocarbons with higher molecular weight. Meanwhile there is a formation of water vapor. The main reaction of the blown products is that the viscosity increases, however, for a given viscosity increase the asphaltene content grows faster than if vacuum distillation process would be used. Therefore the air blown product has different rheological properties. After air blowing the bitumen is stiffer than if it is compared to bitumen from the same crude source, at similar penetration value that is processed by vacuum distillation. Therefore the air blowing is great for specific crudes that have low asphaltene contents and can produce paving bitumen that can be used for roads or in industrial application.[10]
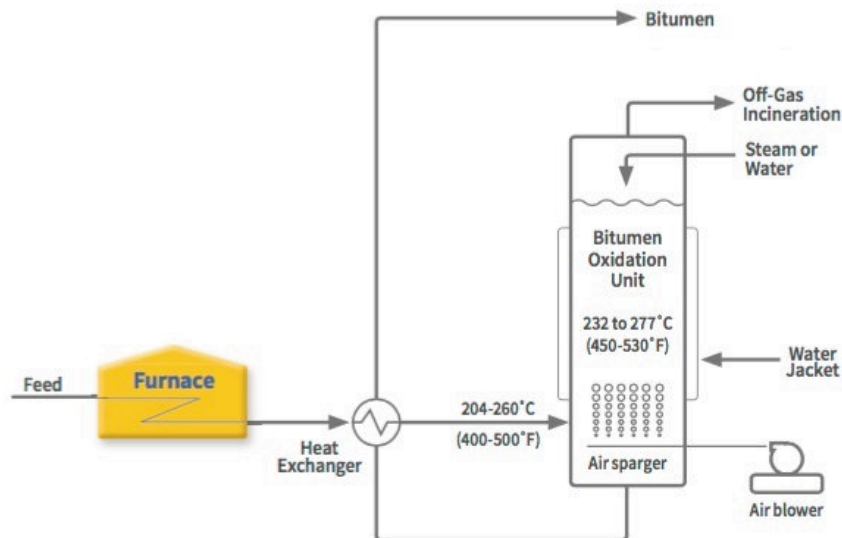
Figure 3: Schematic diagram of the bitumen oxidation process [3]

There is a difference between crude oils how much bitumen is gained from the process depending on what type and from what source the crude oil is from and therefore give different amount of bitumen with different chemical composition after distillation. [7, 11] Furthermore the composition can also change during production or while in use, e.g. due to sunlight and oxygen in the air. [12] It is

best to use heavy or extra-heavy oils for bitumen production due to its properties are high content of high molecular weight hydrocarbons and raised amount of sulfur, nitrogen, oxygen and metals. However there are usually more than fifteen carbon atoms in each molecular chain, which makes the refining process more complex and expensive. Due to its high molecular weight there is a low production of high-octane gasoline and diesel at the refinery. Heavy oils are also characterized by high specific gravity, elevated viscosity, low H/C ratio, and high contents of asphaltene resin, heavy metals sulfur and nitrogen.[7] The distillate yield on three different crude oils can be seen in Figure **4** where extra-heavy oil, heavy oil and light oil are compared.
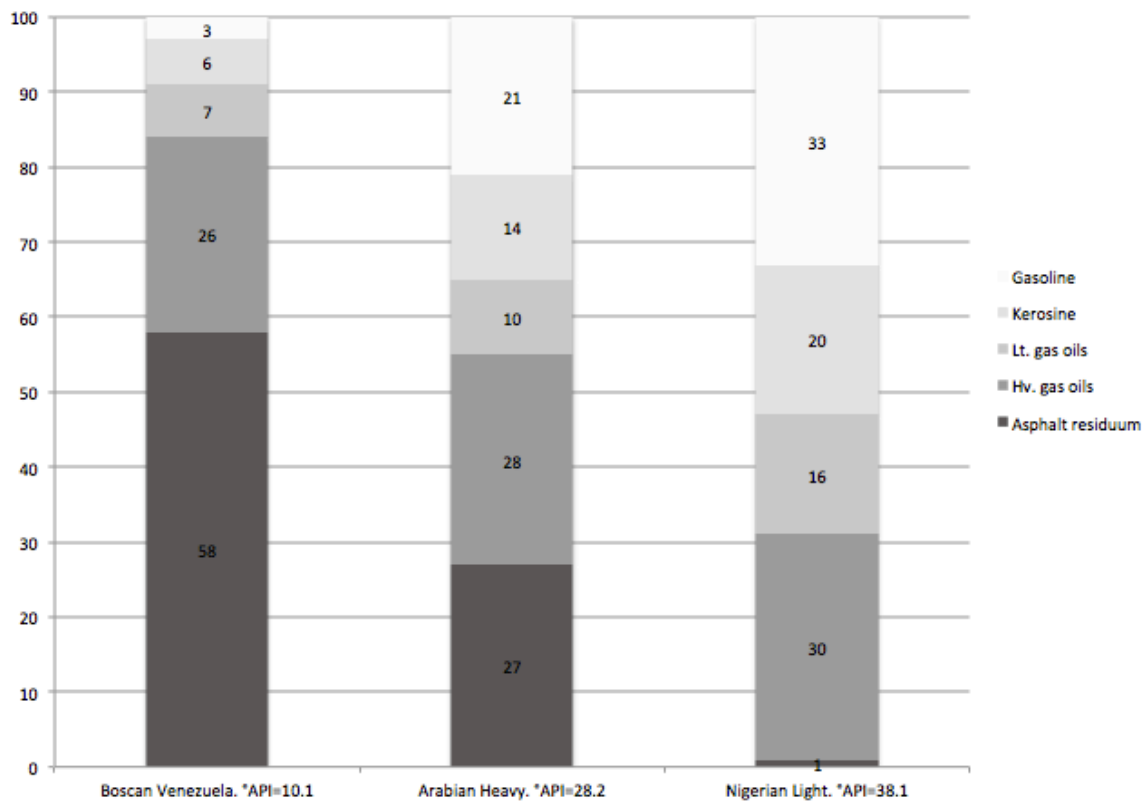
Figure 4: The distillate yield for three different crude oils. [4]

Most tests on bitumen have been used for a long time and are empirical. One of the most common tests are penetration at 25°C. This is a test that gives the stiffness, usually called hardness, at the most common service temperatures of a road. Another common test is called Ring&Ball, it gives the stiffness close to the highest expected temperature in the road, which is called softening point. [2]

Bitumen is classified depending on its hardness. It is divided into hard and soft bitumen. The smaller the penetration, stiffer, the harder the bitumen is. Hard bitumen is used in places where there is great and heavy traffic. Elsewhere the soft bitumen is used. The harder the bitumen is it is less likely for the asphalt to deform. However the asphalt becomes more prone to crack formation if the weather is very cold. Bitumen that is harder demands higher temperature when mixing and installing. The asphalt cools down fast when it rains and in a windy environment. Due to greater temperature difference between the environment and asphalt before it is fully compressed it is more likely for the asphalt to be damaged. That is the reason why it is more risky to install hard bitumen rather than softer one, especially in early spring or late autumn, due to risk of premature damages. [12]

3. Asphalt mixtures

Due to the viscosity of bitumen at ambient temperature, asphalt is manufactured and spread at higher temperature than 150°C. When working at such high temperatures there are greenhouse gas emissions produced. However due to new policies regarding sustainability there have been new developments in the recent years to reduce the effect the asphalt manufacture has on air quality by producing asphalt at lower temperatures. [13] There are four classifications of asphalt that are divided based on the temperatures that they are manufactured and spread. Hot Mix Asphalt (HMA) at temperature 150°-195°C, Warm Mix Asphalt (WMA) at temperature 100°-140°C, Half-Warm Mix Asphalt at 60°-100°C and finally Cold Mix Asphalt (CMA) at temperature 0°-60°C.[14]
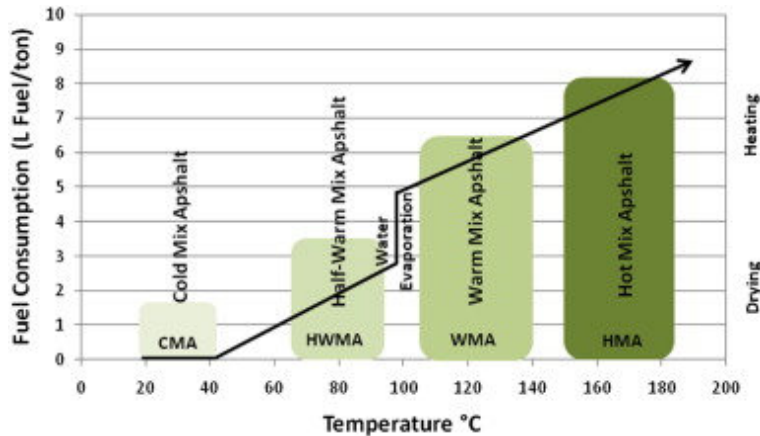
Figure 5: Classification of asphalt mix depending on manufacturing temperature [13]

These new environmentally friendly methods are exciting however the use of CMA is limited and is mostly used on roads that have low vehicle traffic load. Meanwhile the performance of WMA and HWMA is similar to HMA and the use of these technologies is increasing. [13] Using lower temperature technologies is promising but there are also some drawbacks of using WMA and HWMA. The main concerns are the performance and implementation, there are number of issues that need to be researched further. Another drawback is due to less ageing of the binder it is more likely for premature rutting to happen on the pavement surface. Rutting is a type of deformation that accumulates in the wheel paths. There is also a problem with moisture susceptibility that causes lower mixing and incomplete drying of the aggregate. Therefore proper mix design is important to prevent moisture susceptibility. [14, 15]

However using WMA and HWMA there are economical, environmental, paving and production benefits. Economical and environmental benefit is the reduction of energy consumption by having lower production temperatures. This reduces costs of producing asphalt. Another environmental benefit is lower emissions, fumes and odor compared to HMA production. This is especially beneficial for workers and can be very important for paving projects that are not in open air e.g. tunnels. [14, 15] A couple of studies have been made on reduction in gas emissions and their results can be seen in Table 2**.** [14]

13

Table 2: Reduction in gas emissions by using WMA instead of HMA [14]

	Vaitkus et al. [16, 17]	Bueche, N. [18]	Larsen, O.R. [19]	D´Angelo et al. [16, 17]	Evotherm website
CO_2	30-40%	30-40%	31%	15-40%	46%
SO_2	35%	-	-	20-35%	81%
VOC	50%	50%	-	gt; 50%	30%
CO	10-30%	-	29%	10-30%	63%
NOx	60-70%	-	62%	60-70%	58%
Dust	20-25%	-	-	25-55%	-

Example of a paving benefit is that due to the mix temperature is closer to ambient temperature it can have longer haul distances and therefore plant sites can be located far away from the construction site. Furthermore the construction time is shorter due to the reduced temperature difference and therefore it is not necessary to close roads for a longer period time, this is especially important in e.g. airports and high-traffic roads. [14, 15] As a production benefit there is a possibility to use more of Reclaimed Asphalt Pavement (RAP), which is also an environmental benefit. Because of the improved workability, the asphalt mix can contain higher percentage of RAP. It also leads to less aging of the binder that therefore improves the pavement service life, which also counteracts the hard RAP binder.[14, 20]

4. Emulsion

4.1 History of Emulsion

Centuries ago, road surfacing was invented, possibly by the Romans that used large stone slabs to make permanent roads. [2] The ancient Greeks were also familiar with bitumen and its properties. [21] However despite knowing bitumen there were no further developments for the next centuries for road surfacing until the end of the 19th century and early 20th century when the first application of a

binder was used. [2, 21] The first binder was coal tar, not bitumen, which was used to stabilize crushed rock and slag aggregate. The application was that the coal tar was heated and then sprayed hot onto a crushed rock mat to bind the stones together. The use of bitumen in road surfacing is much more recent and developed parallel to the petroleum and car industries at the beginning of 20th century. [2] As cars became more popular governments were pressured to make more and better roads. This lead to innovations both in producing and paving roads. [21]

The use of anionic bitumen emulsion for dust control goes back to 1904 at a race track in France. As cars became popular there was more need for even and last wearing surfaces. Despite an early start hot sprayed tar and bitumen was still more used than emulsion. One possible explanation to this is that tar was in the beginning more abundant than emulsion, especially in Europe, and because tar cannot be emulsified the hot process technique was more used. [2] During the Second World War asphalt technology improved fast due to a growing demands for good surfaces that could handle heavier loads e.g. military aircrafts. [21] Until then the tar, that was then a combination of tar and bitumen, was sprayed in the Western world. Meanwhile in the USA there was a breakthrough where there was a invention of pre-mixed bituminous concrete (asphalt) where special equipment had been developed to mix crushed aggregate with hot bitumen in a controlled way. This was a real success and led to general use of bitumen in the USA and spread from there to the rest of the world where car traffic was increasing. [2] After the war there became more demands of construction of roads due to families moving to the suburbs and therefore road construction became a large industry. [21] At the same time emulsion technology continued to develop. However this was mainly anionic type, which was used in the UK, Germany, Austria, Denmark, India and France. [2] In 1922 British chemists patented anionic emulsion and secured the trademark: Cold Spray that was then in 1924 modified into COLd ASphalt and later shortened to COLAS.[22, 23] In 1951 ESSO in France had an important breakthrough in the development of

cationic emulsion. [22] That lead the emulsion market to higher performance due to cationic emulsion has a chemical breaking behavior that is quicker to settle and has a better performance compared to anionic emulsion that takes time to break because it is based on evaporation of water. [2]

4.2 What is an emulsion?

Due to the chemical properties of water and oil, such as bitumen, they do not mix automatically. If oil and water are shaken together they mix, but are unstable. However it is possible to stabilize the mix by adding emulsifier and then the concluding mixture is called an emulsion. The definition of emulsion is one liquid dispersed of small droplets in another immiscible liquid. A bitumen emulsion is usually considered to be an oil-in-water (O/W) emulsion. That means the continuous phase is water and the disperse phase is an oily liquid. However a portion of the bitumen droplets may have smaller water droplets within them. Thus a better description of bitumen emulsion would be W/O/W (water-in-oil-in-water) multiple emulsion. [24]
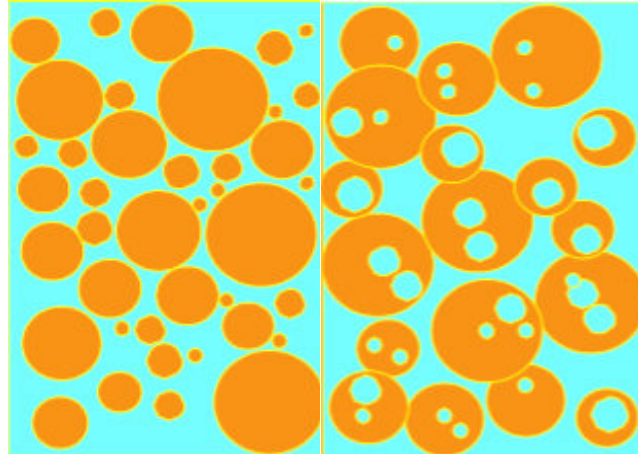

Figure 6: Oil in water (O/W) and Water-in-oil-in-water (W/O/W) emulsion [24]

Because bitumen emulsion is an O/W type, generally the emulsifiers are soluble in the water phase rather than the bitumen. Therefore it would be the best if the emulsifier would be added directly to the bitumen phase since a migration of emulsifier in the water phase would help with the emulsification. During production the bitumen is usually heated up to 120 to 180°C in order to have the appropriate viscosity for emulsification. However most emulsifiers are not stable

at this temperature and therefore emulsifiers are mixed with the water phase since that does not have as high need on thermal stability. [2] The water solution where water has been mixed with emulsifier is often called "soap" solution. The soap solution is mixed with hot bitumen with applied mechanical energy, which sufficiently breaks the bitumen into droplets. This manufacturing process can both affect physical properties and performance of the emulsion. [24]

4.3 Mechanical energy

For the mechanical energy it is possible to use simple mixers, homogenizers, centrifugal pumps or colloid mills. However, for manufacturing of road emulsion colloid mills are the most common to use. A colloid mill is composed of fast rotating conical disc, or rotor, that is placed close to a stationary part that is called a stator. The emulsifier, water and bitumen are forced through a narrow gap between the stator and the rotor which causes dispersion. Normally the capacity is between 10 to 40 ton/h. [2]
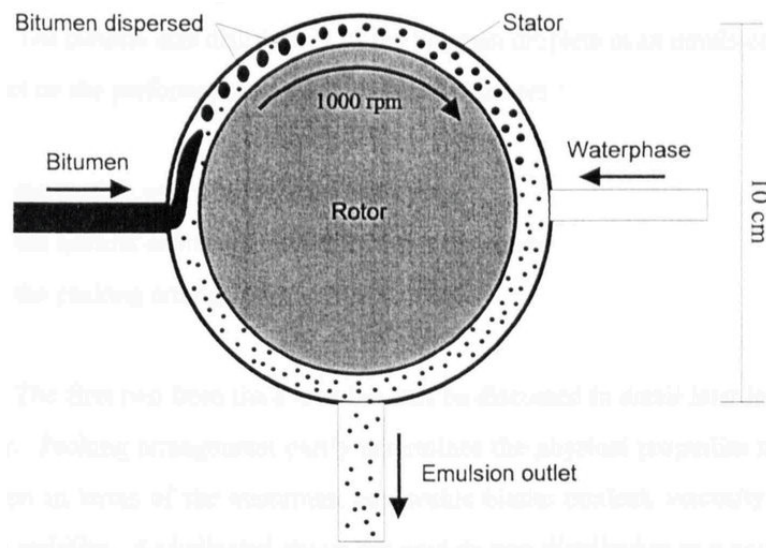

Figure 7: Diagram of emulsification process [6]

4.4 Emulsifiers

Emulsifiers usually lower the surface energy and are called surface-active chemical or surfactants. Surface-active agents have their physicochemical behavior due to they are adsorbed at the interface between liquids and gases or liquid and solid phases. Emulsifiers have a polar hydrophilic head and nonpolar

lipophilic tail. This means that the head is dissolved in water while the tail can be dissolved in oil. The tail is made of hydrocarbons at the range 12 to 18 carbon atoms. They can be categorized in anionic, cationic and nonionic groups based on the charge the head groups take up in water. [25] But the charge it adopts in water can also depend on pH value if the head group type is amphoteric. [24] In addition to the head group they also contain a counter ion that balances the charge. The choice and amount of emulsifier determines the charge and reactivity of the produced emulsion. [25]

Anionic emulsifiers were once utilized more than they are used today but now they are applied for application where basic stones e.g. limestone are used. Then non-ionic emulsions have occasionally been used however they are not produced in any significant amount currently. Cationic emulsion is the most commonly used emulsion due to good adhesion to acidic stones e.g. granite. [2]

Anionic emulsifiers contain negatively charged oxygen (O) atoms and have electrovalent and polar hydrocarbon group as a part of the negatively charged ion when the compound ionizes. [24, 25] In order for anionic emulsifiers to become active they must be deprotonated by a base e.g. sodium hydroxide to increase the negative charge on the head group. See figure. [6]
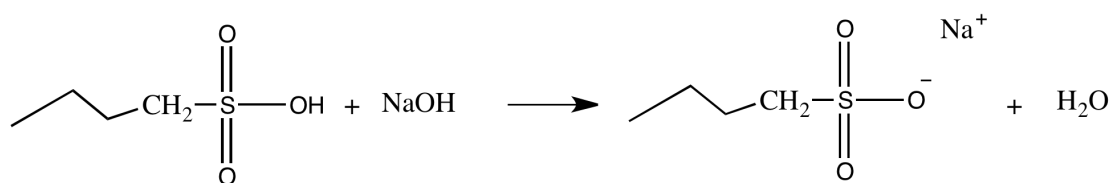

Figure 8: Activation of alkyl sulphonate emulsifier [6]

In the beginning the most used anionic emulsifiers were oleic acid, potassium or sodium soap. However today the most used are byproduct from the pulp and paper industry e.g. tall oil, tall oil rosin or lignin. [2] Anionic bitumen emulsifiers normally are fatty acids or alkyl suphates or sulphonates. [6]

The nonionic surfactants have hydrophilic group that is covalent and polar that dissolves without ionization [25] These surfactants are less immobilized when they come in contact with soil and aggregates that makes the emulsion very stable and have therefore been used when the emulsion has to penetrate through soil, dust and even clay. The advantage of this is that it makes the soil more resistant for water. [2] Nonionic emulsifiers do not have to be protonated or deprotonated. The most common non-ionic emulsifiers are chains of ethoxylate groups (C_2H_2O) and behave, in a way, similarly to H_2O where the molecule is polarized as the electrons become concentrated around the oxygen atoms. That causes the oxygen atoms to become sites of negative charge that leaves the carbon atoms positive. [6]
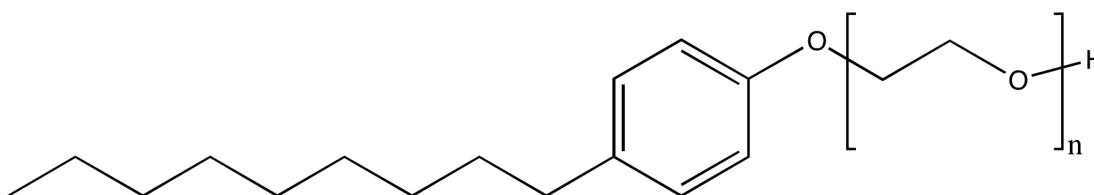
Figure 9: Nonyl phenol ethoxylate [6]

Cationic emulsifiers contain positively charged nitrogen (N) atoms in their head group and have the electrovalent arid polar hydrocarbon as a part of the positively charged ion when the compound ionizes. [24, 25] There are many types of cationic emulsifiers available, which can be a range of fatty amines and their derivatives. They range from simple primary, secondary or tertiary amines to quaternary amine salts, ethoxylated amines, amides and imidazolines. [6] They must be protonated by an acid (except for quaternary amine that carry a positive charge). [6]
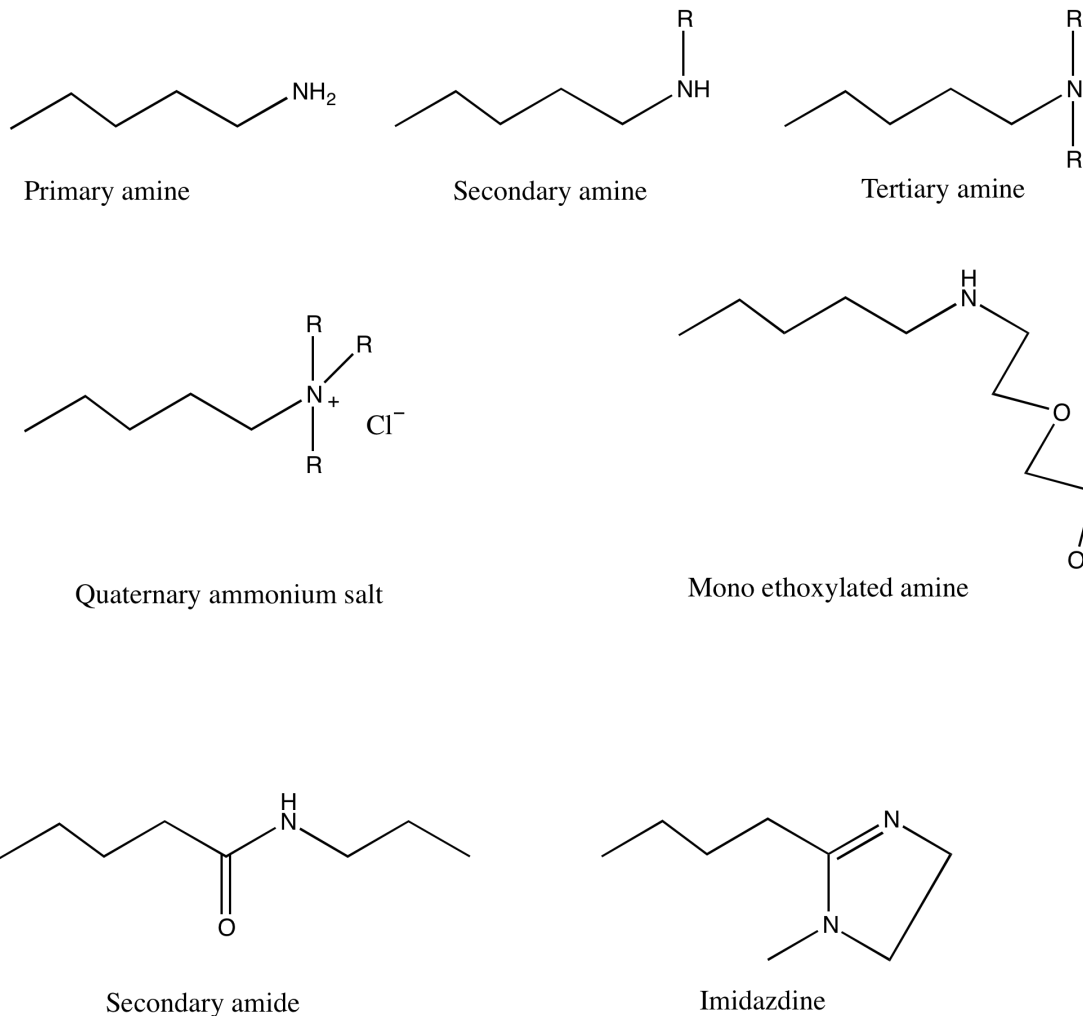
Figure 10: General structure of some amines and derivatives used as cationic emulsifiers [6]

Today commercial emulsifiers for bitumen are often a mix of more than one emulsifier to get the desired properties. [2] For acidification, hydrochloric acid is mostly used by adding it to the soap solution, however it is also possible to use e.g. acetic acid or phosphoric acid. [2] Some emulsifier types do not need to be reacted with acids or alkalis due to permanent head group charges. These products in addition to the nonionic emulsifiers make it possible to produce emulsion that is neutral in pH value.[24]

Figure 11: Activation of cationic emulsifier [6]

4.5 Additives

The goal of adding additives to the emulsion is to make the asphalt better protected against the weather, especially long summer warmth and great cold in heavy traffic. Sometimes it is added to increase adhesi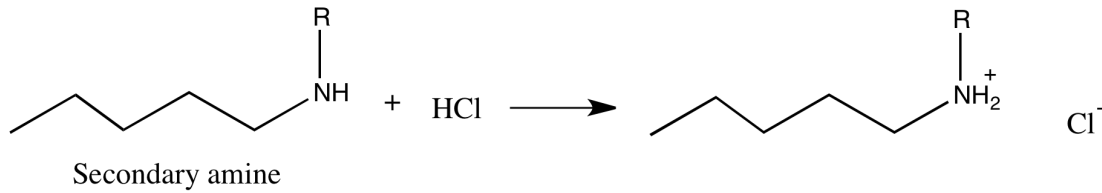on with the aggregates. [12] Adding small amount of salt to the bitumen emulsion can increase the viscosity of the emulsion, which then slowly decreases when the salt escapes. These changes are due to osmotic swelling of the droplets in the emulsion when water is taken into the bitumen droplet. Between 0.1-0.2% of calcium chloride for cationic emulsion and sodium chloride for anionic emulsion, are added to bitumen emulsion. To reduce the osmosis into the bitumen and to minimize the viscosity changes. [24] This stabilizes the emulsion, however, it differs between emulsifiers how much chloride it is possible to add. For example the cationic emulsifier Redicote EM-9 can be stable with 6 times more of calcium chloride than Redicote EM-44. [26]

Solvents are occasionally included in the emulsion to improve emulsification, improve curing rate at low temperatures, reduce settlement or to provide the correct binder viscosity after curing.[24] Usually polymers are used to minimize deformation, improve asphalt properties regarding cohesive strength and reduce the vulnerability to temperature and therefore the risk of thermal cracking at low temperature and resistance to flow at high temperatures. [11, 24] It also helps to reduce the effects of ageing. Polymers enable softer bitumen grades without making it less resistant to high temperatures and improve binder aggregate adhesion. There are two main polymer types that are used in asphalt, i.e. elastomeric polymers and plastomeric polymers. [11] It is also possible to use

latex which is a water-based polymer dispersion that is especially suited to modification of emulsion. The latex type has to be compatible with the emulsion regarding if it is cationic, nonionic or anionic. One of the most used for paving grade emulsions are styrene butadiene rubber, polychloroprene and natural rubber latex.[24] Latexes that are added directly to the asphalt mixer are easy to use since it can be added to the plant without any need for PMB storage tanks. However in general they do not have the equivalent great effect on asphalt properties as plastomers or elastomers. Furthermore, in addition to natural rubber latex, pulverized crumb rubber and waste plastic have been tested and some chemical modifiers e.g. sulfur and organometallic compounds. They have proved to be less successful than elastomeric and plastomeric polymers due to worse performance, cost, health and safety reasons. [11]

Elastomeric polymers can sometimes lead to a decrease in stiffness albeit improvement can be obtained in deformation resistance and cohesive strength. Elastomers reduce the vulnerability to temperature by enhancing the softening point and reducing the brittle point. This means that modified binders have higher viscosity and are less brittle at lower temperatures. This results in that the asphalt is unlikely to thermally crack in the winter and is less disposed to permanent deformation that happens in the summer. [11]

Examples of plastomers used are ethylene methyl acylate, polypropylene (PP) and polyethylene (PE). These materials have been shown to be less successful because the asphalt becomes too brittle and stiff. [11]

Thermoplastic elastomers have also been used. They stiffen the bitumen at high temperatures while it is less brittle at low temperatures due to their rubber characteristics. [3]

The use of polymer bitumen emulsion increases the lifetime of the asphalt where the bitumen is more elastic and has increased adhesion and better grip with the

aggregates. Furthermore the temperature has less effect on the road i.e. it is less likely for the bitumen to bleed in the summer so the roughness of the surface remains. It also reduces the risk of fretting in the summer because the binder is not as brittle. Consequently it is expected for surface dressing with polymer as an additive in bitumen emulsion to work for a longer period of time. [27]

It is important to consider weather conditions when paving polymer-bitumen emulsion, especially temperature and humidity. Polymer bitumen emulsion can break faster than normal bitumen emulsion and make good adhesion so it is possible to open the roads again sooner. [27]

4.6 Breaking and setting processes

For emulsion to return from droplets to continuous bitumen the emulsion must coalesce.[6] Because the coalescence and breaking mechanism are so complex they are still not fully understood that results also from shortcomings in current experimental methods and models to examine and explain them. However there have been theories presented. [28, 29]

It is believed that there are forces acting between dispersed droplets are e.g. van der Waals interaction, electrostatic forces and stearic repulsion. These forces with energy differences govern the physico-chemical process that breaking and curing of emulsion is. A theory called the DLVO proposes that stability of a colloidal system is decisive by the sum of van der Waals attractive (V_A) and electrical double layer repulsive (V_R) forces that are between the droplets when they come close to each other due to the Brownian motion they are subjected to. The theory suggests that an energy barrier prevents two droplets to come close to one another and adhere together, that is due to repulsive forces.

Illustration on how the forces are between two particles as a function of separation distance can be seen in Figure 12. The figure displays when the separation distance is low the force between two adjacent droplets is negative, that implies that the attraction between the particles is strong so they can coalesce together. Meanwhile, when the distance increases the repulsive forces become stronger. If the droplets manage to overcome the barrier the force will attract them together so they will irreversibly adhere together. [30]
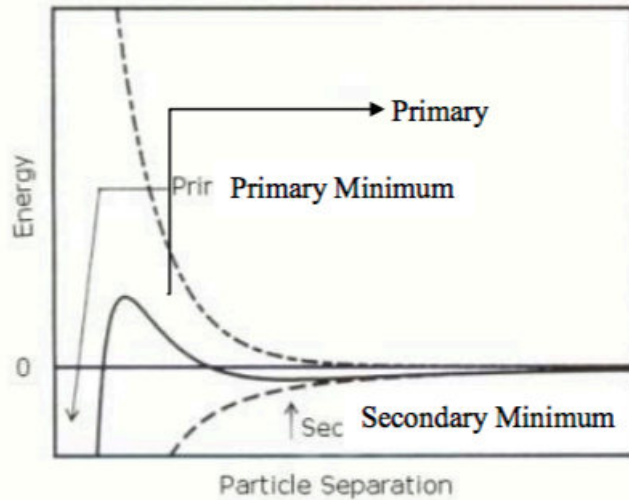
Figure 12: Schematic figure of how particle free energy is as function of separation distance [30]

On Figure 12 there is also demonstrated that there is a possibility of formation of secondary minimum. That is a weaker flocculation that can be reversed. [30] It can happen by e.g. agitation, dilution or emulsifier. It is possible because the droplets form agglomerates without losing their individual solidarity. However, with time the water layer between droplets in a floccule will thin and droplets coalesce so the droplets merge together into bigger droplets and this cannot be reversed. [24, 29] Factors that reduce the charge on the droplets or force the droplets together accelerate flocculation and coalescence e.g. settlement under gravity, evaporation of water, shear or freezing. This happens faster for low viscosity asphalts than asphalts with high viscosity. [24]
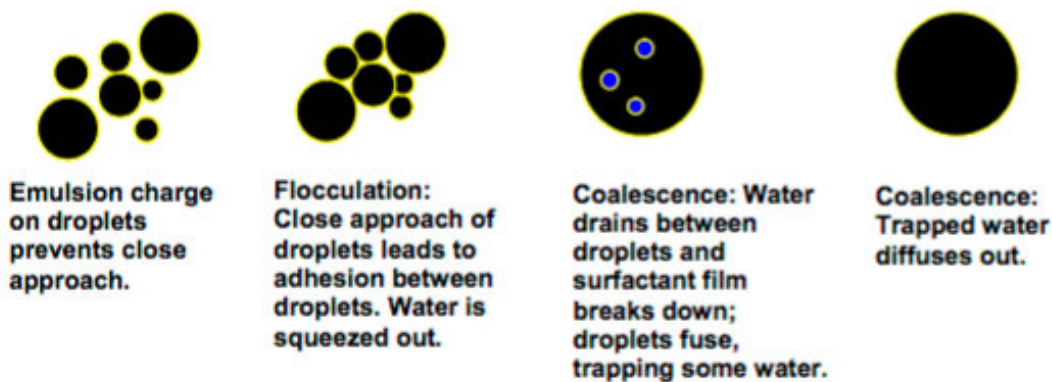

Figure 13: Stages of breakdown of emulsion [24]

When droplets get enough energy to overcome the barrier and approach closely they flocculate. [24] Certainly that is the final goal for the emulsion droplets, so they can coalesce. [24, 29] However, the potential repulsion of the emulsion droplets must be enough to prevent premature coagulation. [30] Because coalescence is only wanted after it comes in contact with aggregates and is placed on roadway because the adhesion can be poor if it starts earlier and if water is present at the interface. [24, 29] This can lead to deficient adhesion, reduce the mechanical strength and it can hinder the final curing by skin formation, which will reduce water evaporation. [24] Premature coalescence might happen due to there are too many fines or highly reactive mineral surfaces, which might be connected to Alkali-Silica-Reactivity. [28] Furthermore if it starts raining before the emulsion is starting to break it will not stick to the aggregates and if the emulsion has too high viscosity it may also not stick to the aggregates.[12] During coagulation a continuous film of bituminous binder is developed that is followed by curing or setting of the binder. This determines how much mechanical strength the cold asphalt will have. [29] While curing water leaves the bituminous material after the breaking of emulsion is completed or at least sufficiently initiated. It can happen by evaporation and it can also be diffusion controlled. Therefore the kinetics are controlled by the rate of diffusion of water through the coalescing binder. The final result of curing is a continuous cohesive film which will hold aggregates in place. [30] The speed of setting and curing, that is often named the breaking rate, has is influenced by reactivity of emulsion, reactivity of aggregates and environmental factors e.g. temperature, wind speed, humidity and mechanical action. It determines the behavior of the emulsion and for different applications there are different breaking rates suitable. [6, 24]

A theory by Gaestel [31] proposes that there are two mechanisms of anionic emulsion breaking. The first is if anionic emulsion is mixed with positively charged calcareous aggregates emulsifier and calcium ions in the aggregates form salt. This removes the emulsifier from the emulsion, which leads the

emulsion to break. However with siliceous aggregates that are negatively charge there is the inorganic cation that is adsorbed to the aggregate surface. Due to the loss of counter ion in the emulsion,it will destabilize and break. The breaking rate is therefore proportional to the inorganic cation concentration. [6]

For cationic emulsion there are a couple of theories how it breaks into negatively charged siliceous aggregates. [6] Wates and James [32] claim that there are three possible processes called emulsifier abstraction, deprotonation and droplet migration. In the first process, abstraction, the aggregate abstracts the emulsifier from the bitumen and water interface. When the mixture loses the emulsifier the emulsion becomes unstable which leads to coalescence of the droplets. [6]
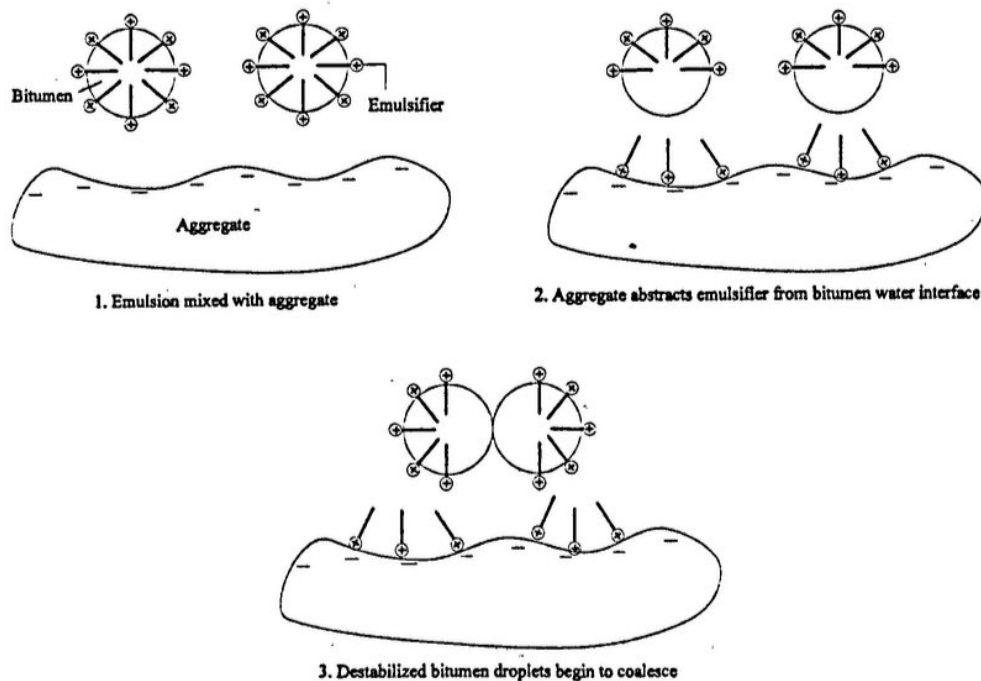
Figure 14 Breaking mechanism of bitumen emulsion by emulsifier abstraction[6]

In the second process there is a deprotonation of the acidified emulsifier by the basic sites on the aggregate surface. This causes deactivation of the emulsifier, which leads to breaking of the emulsion. [6]
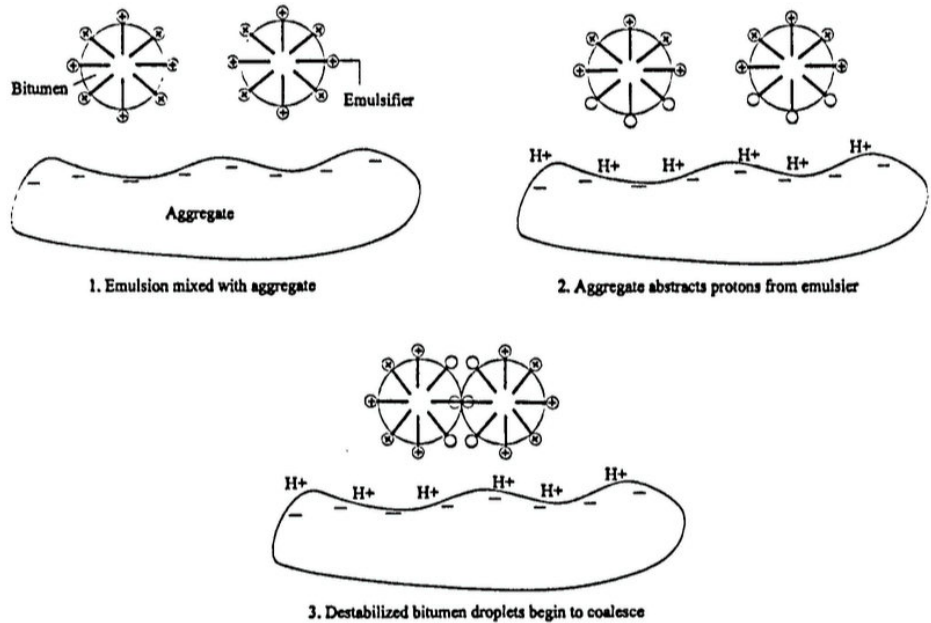
Figure 15: Breaking mechanism of bitumen emulsion by emulsifier deprotonation[6]

Droplet migration is the final and most important process. Where the positively charged emulsifiers on the surface of the bitumen droplet lead to attraction between the droplets and the aggregate. Then the droplets spread over the surface of the aggregates with support from the surfactant. The surfactant act as adhesion or anti-stripping agents and this process is therefore very beneficial and is the main reason why cationic emulsifiers are more popular rather than anionic emulsifiers. [6]
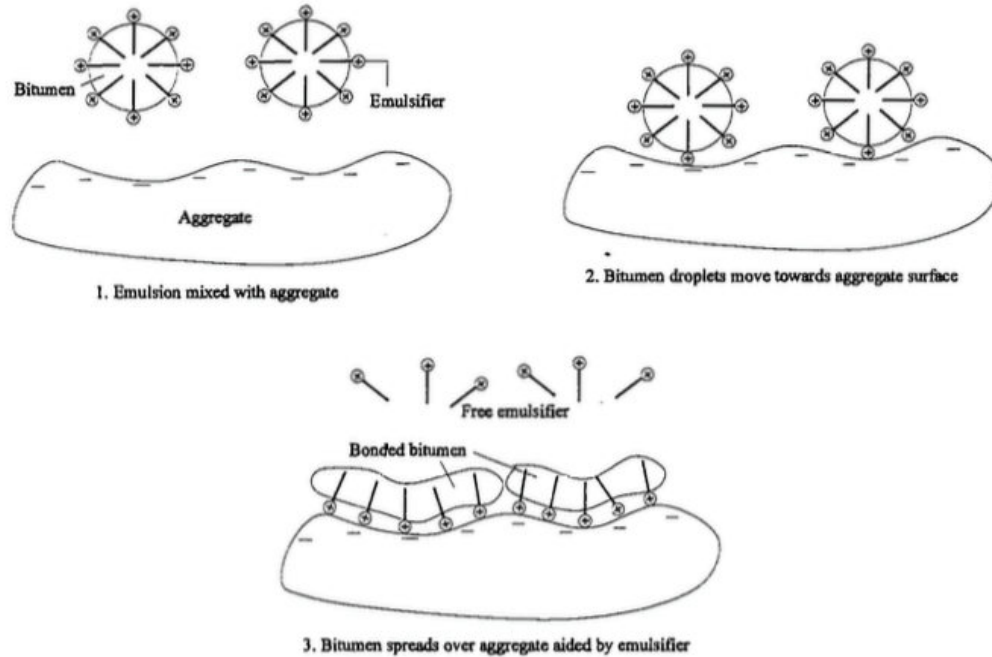
Figure 16: Breaking mechanism of bitumen emulsion by droplet migration [6]

It is very likely that more or less all of these processes happen when bitumen emulsion breaks, depending on the conditions in the system. [6]

However a study by Plotnikova [33] has another theory that proposes that the free emulsifier in the emulsion is adsorbed onto the aggregates and then aggregates adsorb emulsifier from the bitumen droplets. The aggregate becomes hydrophobic because of desorption of emulsifier and is therefore able to attract bitumen. Based on this process the emulsion breaking rate is dependent on the adsorption rate of emulsifier to the aggregate that is controlled by the surface area and chemical properties of the aggregates and bitumen emulsion. The theory is based on chemisorption that includes ion exchange between emulsifier and aggregates. However there are not enough sites on the aggregate available for all the emulsifier to adsorb all the emulsifier chemically and therefore it is also necessary to have physical adsorption. Physical adsorption happens due to attraction between the positively charged emulsifier and the negative sites of the aggregate. [6]

If there is great amount of emulsifier free in an emulsion it will attach to the aggregate causing that the binder cannot break onto the aggregate. Instead there is bad binding of the total mixture due to that the bitumen coalesce away from the aggregate, which will lead to bad adhesion, raveling and resistance to fatigue. However if there are low amounts of free emulsifier the bitumen droplets will break onto the aggregates and therefore ensure a good binding. [6]
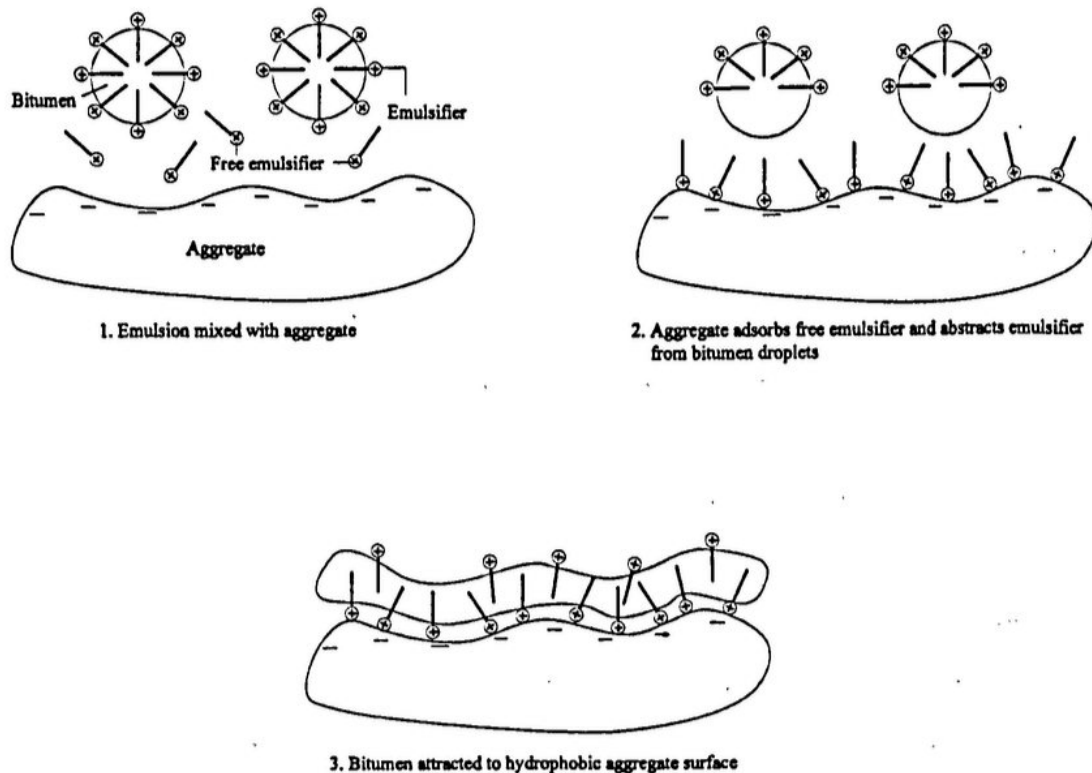
Figure 17: Breaking mechanism of bitumen emulsion by emulsifier adsorption[6]

For the nonionic emulsion it is harder to predict a mechanism due to no electrochemical interaction and is therefore probably more related to how the aggregate can absorb water or evaporation of water. [6]

One factor that affects the breaking rate is the particle size distribution. The smaller droplets the emulsion has the larger surface area is at the interface between the bitumen and water. Increased surface area increases the number of available reaction sites that causes the breaking process to happen faster. [6]

Furthermore the emulsifier adsorption at the interface of bitumen and water has greater capacity. On the contrary there is more of free emulsifier in the water phase if the particle size distribution is larger. Hence that will slow down the breaking process because the free emulsifier available will use all the active sites of the aggregates. [6]

Most naturally occurring mineral aggregates that are used in road construction have negative surface charge. Therefore there is a relationship between the zeta potential of aggregates and the surface area and zeta potential of cationic surfactants. Examples of negative surface charged aggregates are e.g. granite, limestone, marble, dolomite, silica, sandstone, basalt and quartz. Due to anionic surfactants have a negative charge like most aggregates, and nonionic surfactants have no charge, they both settle the emulsion on the aggregates surface primarily by evaporation and absorption of the water phase. [25]

4.6.1 Zeta potential

The bitumen-dispersed phase has particular properties regarding electrical charge and by knowing them it is easier to understand the behavior of the emulsion colloidal system. [34] The net electrical potential difference between the dispersed medium and the bulk aqueous solution is called zeta potential. The zeta potential is developed by the adsorption of ions onto the bitumen that is a colloidal particle surface. It is determined by the motion of colloidal particles in an electrical field. [25, 35] In the solution around the dispersed bitumen droplets is a double layer of ions and counter-ions. [25] It is possible to determine the zeta potential by placing the colloidal particles in an electric field and measure the movement energy, this is usually measured in millivolts (mV) with a microelectrophoresis device. Looking at the behavior of emulsion with respect to measuring the zeta potential is similar to what is observed when mixing emulsion and aggregates.[34] Factors that affect the zeta potential are e.g. ionic strength, concentration of additives, temperature and the most important pH value. [35]

Generally the higher the zeta potential is the more cationic the emulsion is and then the emulsion breaks more rapidly. While lower zeta potential provides a more stable emulsion with slower breaking speed. Hence the breaking speed of emulsion is directly proportional to the zeta potential of the emulsion.[34] The degree of attraction and quantity of counter-ions is dependent on the pH value, concentration and ionic intensity of the emulsifier. The ability of the colloidal particles to adsorb ions is affected by the pH of the solution, which affects the double layer and thus the zeta potential. Another factor that affects the double layer is the concentration of the emulsifier. When emulsifier concentration is increased the double layer gets compressed and therefore the zeta potential decreases. [25]

The stability of the emulsion and the ability of the charged bitumen particles are essentially affected by this double layer. The greater the double layer the bigger the zeta potential and therefore the faster the charged particle moves in an electric field. Most of the time a large zeta potential denotes larger repulsive forces between the individual particles in an emulsion, which causes good stability. The zeta potential contributed to the bitumen droplet from the emulsifier is therefore one of the important factors that help in keeping the bitumen droplets dispersed evenly. [25]

4.7 Particle size distribution

The internal water phase in the oil droplets greatly influences the viscosity of the emulsion, particularly viscosity during storage. Another factor which influences viscosity and storage stability is the distribution of particle sizes in the emulsion. That is influenced by the recipe, mechanics and operating conditions of the emulsion plant. If the average particle size is larger it leads to lower emulsion viscosity, likewise broad or bimodal particle size distribution also lowers viscosity. Packing arrangement of the droplets determines as well how much binder can be in the emulsion, the viscosity and storage stability. [6]

Particle size also affects the emulsion performance by affecting the surface area of the emulsified bitumen, the amount of free emulsifier in the water phase and the packing arrangement of the droplets. [6] Generally the performance gets better with smaller particles. When concentration of emulsifier is increased the particle size of the emulsion gets smaller.[24]

The performance of the bitumen emulsion is also influenced by the control of the coalescence and breaking process. Therefore climatic conditions have to be taken into consideration when deciding which emulsifier and additives should be used with intended types of bitumen and aggregate. [28]

The wider the particle size distribution the less stable is the emulsion. Furthermore as suggested by the Stokes law the larger particles are more likely to settle that can lead the particle size to increase even more while storing. [6]

$$v = \frac{2gr^2(d_1 - d_2)}{9\eta} \qquad (2)$$

where v = velocity of settlement (ms-1), g = acceleration of gravity (ms^{-2}), r = radius of bitumen droplet (m), d_1 = specific gravity of the dispersed phase (bitumen), d_2 = specific gravity of the dispersing phase (water), η = dynamic viscosity of the dispersing phase (water) (mPa·s) [6]

It depends on the application if slow or fast breaking is wanted. Fast breaking is desired for surface dressing, slurry surfacing and various types of sealing. However slow breaking is wanted when e.g. mixing grade asphalt is stored to use late for patching. Nevertheless all emulsions have the common ground that once they are in place on the road they should break and heal fast. [2]

4.8 Stability
The emulsion must be formulated in the way so it stays stable when being stored and transported but also sufficiently unstable so it breaks when used for

application. [2] There are many processes that destabilize emulsion e.g. sedimentation, creaming, Ostwald ripening, flocculation, coalescence and phase inversion. [29]

Five types of bitumen emulsion stability is recognized, those are: storage, chemical, freezing, mechanical and mixing. Some are related to each other while others have no relation. There are two parameters that are very important no matter which application is chosen. One parameter is breaking process or phase separation when mixed with aggregates or existing asphalt concrete layers and the second is stability both chemically and for storing. [2]

4.8.1 Storage stability

Having slow agitation in the storage tank normally solves the storage stability of emulsion. However too intense agitation can cause the emulsion to break. There are four properties that control storage stability: bitumen density, bitumen content, freezing and maximum particle size. [2]

The density of bitumen is approximately 0.95 to 1.10. If there is a density difference between bitumen and water, creaming and sedimentation happen. Because the density for both materials is almost the same it is often possible to find temperature where the density is almost identical which is usually around 70°C. Furthermore if the density of bitumen is very high it can be better to increase the density of water by adding salt e.g. calcium chloride. However, it is important to note that chemical stability of the emulsion decreases with high temperatures and high salt content. High temperature decreases the viscosity of the bitumen and therefore speed coalescence while high salt content decreases the electrical double layer which causes the repulsive force between the bitumen particles to decrease. [2]

Bitumen content affects the storage stability of the emulsion. Generally it is easier to store emulsion with high bitumen content (67 to 70%) because more

space is filled by the bitumen phase so there is no room for sedimentation or creaming to take place. However for emulsion with low bitumen content (40 to 60%) the distances between the bitumen drops are so long that only Brownian movements may keep the emulsion stable. These movements are too weak for particles that are larger than 10 μm thus it is impossible to prevent sedimentation or creaming. [2] Freezing generally ruins oil-in-water emulsions and bitumen emulsion should therefore not be stored below the freezing point of the continuous phase. However it is possible to add antifreeze liquids e.g. ethanol or ethylene glycol if necessary to use below freezing point. [2]

If the particles in the emulsion are approximately larger than 10 μm it becomes more sensitive to mechanical stress. This increases the risk for the emulsion break while pumping, transporting and stirring. Furthermore the expected storage time also becomes shorter because of Ostwald ripening where the smallest particles coalesce into the largest ones. [2]

4.8.2 Chemical stability

Chemical stability is the stability against breaking and coalescence. There are many factors that affect the chemical stability, some are related to the production e.g. pH, emulsifier type and amount and bitumen content. While other factors are connected to the handling of emulsion e.g. mechanical stress, pumping, stirring and transportation. [2]

5. Aggregates

When constructors are choosing aggregate for road construction the main criterion that they look at is cost, especially cost of transporting aggregates significant distances. Therefore the aggregates that are used usually reflect the local geology. [36] This can be very different between two countries. For example the most common rocks in Sweden are e.g. granite, granodiorite, sandstone and marble. [37] While 90% of rocks found in Iceland are basalt with the other 10% are e.g. Iceland spar, icelandite and zeolite. [38]

However the important aggregate properties to look at are size and grading, cleanliness, toughness, soundness, particle shape, surface texture, absorption and stripping. [39] There is certain size and grading of aggregates wanted for different applications of asphalt. It is necessary for the aggregates to be clean due to foreign or deleterious substances that can cause the aggregates to be unsuitable for paving. [39] Toughness is also necessary for aggregates so they can resist being crushed or disintegrated during mixing, placed, compacted and handle being under traffic load. Soundness, that is similar to toughness, is the ability to resist decay due to natural elements e.g. weather. The particle shape of aggregates also influences the asphalts' strength and workability. Furthermore it also affects the density achieved through compaction. The irregular particles e.g. crushed stone are prone to "lock" together and prevent dislodging when compacted. The asphalt gives better results if it has rough texture because then it has higher strength. Smooth texture is easy to coat however they usually do not work as well as rough surfaces. Therefore surface textures of aggregates are important since workability and pavement strength are influenced by it. Furthermore, the asphalt gets a better "grip" for rough surfaces rather than smooth surfaces. Some porosity of an aggregate is desired where it allows the aggregate to absorb asphalt and thus forms a bond between the particle and the asphalt. However if the aggregate is highly absorbant it is usually not used. Stripping is when the asphalt film separates from the aggregates due to the action of water. This can also happen if aggregates are coated with too much dust causing poor bonding. Aggregates that are prone to stripping are generally not suitable for paving unless by adding anti-stripping agent as well. [39]

It is important to choose aggregate for the wearing layer that is strong and has great weather and wear tolerance. The strength of the rocks depends on e.g. mineral size, density and alteration. Hence, rocks that are porous have less strength than those that have high density. Alteration has also great affects on quality of rocks to use for construction due to weathering tolerance is lower with greater alterations.[40]

6. Adhesion

The performance of asphalt mixture is greatly influenced by the composition of the mixture, mixing and compaction processes, internal structure and the properties of the materials. [28] Furthermore the durability of asphalt mixtures depends partially on adhesion between bitumen and aggregates. [36] Where lack of adhesive bond between emulsified binder and aggregate can cause loss of aggregates. [30] Definition of adhesion between two dissimilar surfaces is when valence forces or interlocking forces hold them together. Adhesion determines the propensity of molecules of two materials to cling to one another. [41] Where the physical and chemical properties of the bitumen and aggregates influence this performance of the mixture. [42]

Diverse parameters influence the adhesion between bitumen and aggregates e.g. surface free energies of both binder and aggregates, mixing temperatures, surface textures, nature of the minerals and their surface chemical composition, additives in the binder phase and it is also influenced if the aggregates are clean or dusty and dry or in presence of moisture on the surface aggregates. [28] Adhesion is also one of the crucial criteria for water damage resistant. [42]

There are four theories that explain the adhesive bond between bitumen and aggregates: mechanical theory, chemical theory, weak boundary theory and thermodynamic theory. The mechanical theory suggests that the adhesion is affected by physical properties of the aggregate e.g. porosity, texture and surface area. The chemical theory indicates that the adhesion is dependent on pH value and the functional groups of both the bitumen and aggregate. The weak boundary theory indicates that rupture on the bitumen asphalt interface always takes place at the weakest link. Then the thermodynamic theory is focused on the attraction between the aggregate, bitumen and water that is caused by differences in surface tension. These mechanisms are not independent and many researchers agree that there is a combination of mechanisms that takes place. Furthermore, there are many factors that affect the adhesion of the binder

to the aggregate e.g. interfacial tension between the binder and aggregate, chemical composition, binder viscosity, surface texture of the aggregate, porosity of the aggregate, cleanliness of the aggregate, temperature of the aggregate and moisture content when mixed. [41]

The bitumen properties can affect its bond with the aggregate e.g. polarity, constitution, viscosity, film thickness and surface energy. Furthermore, the strength of the asphalt mixture in the presence of moisture is also affected by the chemical nature of the binder and processing techniques. [41] Aggregate properties that affect the adhesion are e.g. size and shape, porosity, surface area, silica content, chemical constituents, acidity/alkalinity, adsorption surface density and polarity. [12, 41] It is important to have the aggregate clean due to that moisture and dust can greatly reduce the bond strength between bitumen and aggregate. If dust coatings are present on the aggregate it hinders the aggregate to become completely wet by the bitumen. This is because the bitumen adheres to the dust coating instead of the aggregate and therefore it is essential to wash the aggregates properly. Aggregates are classified into hydrophobic (greater natural affinity for bitumen (oil) than water) and hydrophilic (greater natural affinity for water than bitumen). Acidic aggregates are most often hydrophobic and basic aggregates are hydrophilic but there are few, if any, aggregates that can completely resist the stripping of water.[41] Therefore the best adhesion is not achieved until the aggregates are fully dry and that can take a long time. [2] Depending on type of aggregates they react differently in the adhesion process. [42] The properties of the materials are very important for the performance of the asphalt mix e.g. surface texture of the aggregate influences how well the aggregate can be coated, which is necessary to prevent stripping. [42, 43]

Lack of compatibility between bitumen and aggregate that is if there is not enough adhesion and/or loss of cohesion in the bitumen, in the presence of water is one of the most important causes of moisture damage. [43] This means

the loss of stiffness and strength which is caused by moisture under mechanical loading, appears in, a phenomenon called stripping. [41] Stripping is when the bitumen film is replaced by water from the aggregate surface due to lack of adhesion between the materials. This can greatly affect the performance of the asphalt mix. Moisture damage is considered a significant source of distress in asphalt pavement and causes great maintenance cost yearly. Even though not all damage is directly caused by moisture, its presence increases existing distresses. [43] Consequently the scale and extremity of distresses e.g. rutting, fatigue, cracking, raveling and potholes becomes greater. [41] It also causes the degradation of mechanical properties of the asphalt i.e. it loses its stiffness and mechanical strength that leads to pavement failure.[43]

There have been attempts to control moisture damage by limiting the percentage of air voids that results in limited access of water to the bulk of the asphalt mixture. However, even though the percentage of air voids is low, there is evidence of damage caused by infiltration of water. Which means that total air void content does not give an inclusive measure of the rate of moisture transport in to asphalt mixtures. [44]

Moisture degrades an asphalt mixture by three mechanisms: by loss of cohesion with the asphalt, failed adhesion bond between aggregate and asphalt or degradation of aggregate. In addition to that if water is present in the mixture, it can affect its performance by remaining static at the interface and voids and by flowing between interconnected voids.[41]

7. Applications

There are numerous pavement applications applicable for bitumen emulsion. Such as tack and prime coats, fog seals, spray applications e.g. surface dressings or chip seals, mixing with stone material e.g. in slurries, micro surfacing and cold mix paving, which all have different characteristics. [6, 29]

For example fog seal are used as a surface treatment where it is used to seal minor cracks or on surfaces that have lost binder and chippings or raveling. They can extend the life of asphalts considerably. Meanwhile tack coat is used as a layer to bond between old surface and new applied asphalt. It is a very light spray of diluted bitumen emulsion that usually contains around 50% bitumen. [6] It is a bitumen emulsion used as a pre-layer to get good adhesion between the existing pavement surface and the new asphalt layer. Doing this increases the strength and durability of roads that have many asphalt layers. The tack coat emulsion should have a good storage stability and low viscosity. Low viscosity is crucial to have good wetting of the existing surface and so the emulsion can penetrate through remaining layers e.g. dust or fines on the old surface. [2] However here the main focus will be on surface dressing.

7.1 Surface dressing

Surface dressing is a surface treatment that is used to provide a dust free wearing surface over a granular base and waterproof surface so the rainwater does not filter into the pavement, it delays disintegration of the road surface and serves as an improved coat for regular preservation of bituminous surfaces. [45] Furthermore it increases skid resistance and roughness of the road surface to increase safety. [27]

Surface dressing is sometimes called chip seal, it is a technique that is used for maintenance of old roads either by making new wear layer or by sealing cracks. It is an interesting technique due to it is relatively cheap and it is possible to pave many square meters each day. The spraying temperature of bitumen emulsion for surface dressing depends on the equipment used however it should be between 50°-80°C. [45] The emulsions for surface dressing are rapid setting cationic emulsions and usually have high bitumen content (68-71%) so the emulsion has high viscosity and there is little amount of water that has to be evaporated. It is important that the binder sets quickly so the traffic is not stopped for too long and hence it is possible to remove extra chips by sweeping. [2, 6]

The emulsion viscosity in surface dressing should be high enough to avoid run-off while spraying on the surface. The emulsion should also have a good reactivity. This is a phenomenon that happens before the emulsion loses its water, and it is related to adsorption of emulsifier to the stone surface. Good reactivity means it should have good adhesion and break fast, but not too fast, after coming in contact with aggregates. The emulsion should have enough time to wet the stones before breaking takes place but coalescence should also happen fast. That means that it is expected that the emulsion film evaporates water fast. [2]

Surface dressing is used in a couple of ways. It can be used as a new wearing course on unbound surface. It can also be used as a new wearing layer on an older wearing course to increase skid resistance and durability. [27] There are different types of the surface dressings where amount of layers of aggregates and emulsion can vary. [2]

Single-coat surface dressing is made by spraying a layer of binder on pavement surface that has been prepared previously and subsequently one layer of aggregates and then rolled over it. [45] This method uses the least amount of material but has a limited tolerance to stresses. [46] It can be used on roads with traffic up to 2000 Annual average daily traffic (AADT) with 8/11 mm or if there is not great strain on the roads e.g. intersections and turns 11/16 mm aggregates can be used. However if 11/16 is used it is more recommended to use racked in surface dressing if the traffic is more than 500 AADT.[27]
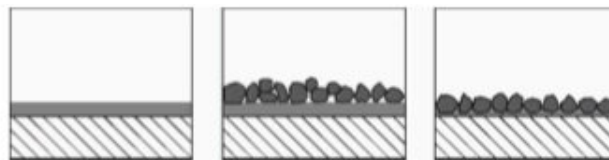

Figure 18: Schematic diagram of single surface dressing [47]

Double surface dressing is formed by making a single-coat surface and then add another layer of binder and then aggregates are spread and rolled. The second

layer of aggregates must be smaller than the first layer. [45] The requirements of high viscosity is not as necessary for double surface dressing. [2] Double surface dressing is used where there is a lot of traffic e.g. intersections and sharp turns etc. and where the traffic speed is fast. [27] It is more robust then racked in and is used on binder lean surfaces. [46] Furthermore it is also used on unbound and recycled surfaces. [27]
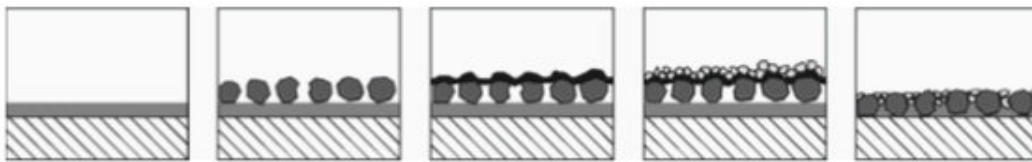
Figure 19: Schematic diagram of double surface dressing [47]

Another possible application is called racked-in surface dressing where emulsion is sprayed and then it is laid out large stones on the emulsion and then smaller stones, this is expected to lock in the large stones. [2] Racked-in surface dressing is used to have the aggregates more stuck/fixed and decrease the risk of aggregates sticking to tires. [27] It is mainly used on roads where traffic is heavy or fast. Aggregates of size 8/11 mm are used with 2/6 mm or 11/16 mm aggregates with 4/8 mm if traffic is more than 500 AADT. The method is used to decrease the amount of bigger aggregates, around 10%, and then increase the bitumen emulsion to stick to the smaller aggregates. This is especially good to prevent defects due to rain after paving. [27]
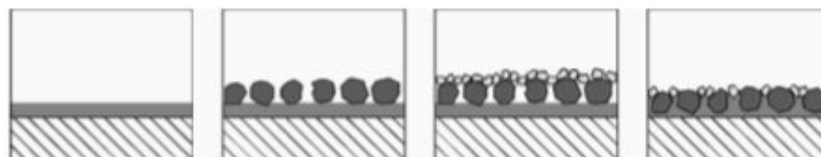
Figure 20: Schematic diagram of racked-in surface dressing [47]

In inverted double dressing emulsion is first sprayed and on top of that small chippings are laid and then another layer of emulsion is sprayed out that is followed by bigger chippings. This technique is suitable on roads where surface texture is not the main problem.[48] Inverted double surface dressing is used on

very hard surfaces or roads that have uneven hardness. [46] For this type of surface dressing polymer bitumen emulsion should be used, unless if the lower binder layer if it is paved on top of a cement layer, then it is recommended to use bitumen emulsion without polymer. [27]
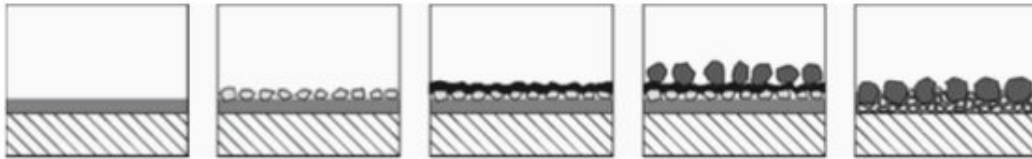

Figure 21: Schematic diagram of inverted double surface dressing [47]

Sandwich surface dressing is used on an old surface with high bitumen content, regardless of amount of traffic and speed. [27] First large chippings are laid and then the emulsion is applied on top of them and finally smaller chippings are applied on the emulsion. This is suitable for roads of irregular hardness e.g. heavily patched or where fatting up has happened in the wheel tracks. [49] When ready, it looks like double surface dressing but experience shows that it is more risk of scabbing from the base course if it is short of bitumen. [27]
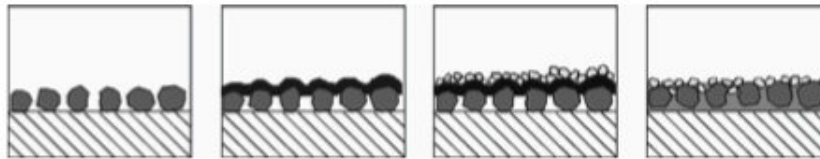
Figure 22: Schematic diagram of sandwich surface dressing [47]

7.2 Defects of surface dressing
Most defects of surface dressing happen in the first twelve months and after that period its durability is assessed visually.[47]

Defects where mosaic, which is the arrangement of the chippings so they are shoulder to shoulder contact and are therefore supported laterally, is covered by binder are: bleeding, fatting up and tracking. [47] Bleeding is when binder goes up to the surface so it loses its roughness and decreases the skid resistance. The most common reasons for bleeding are too much binder, low viscosity of binder and too high temperature. Fatting up is when the aggregates go down to substrate so the binder is on the surface. Likewise for bleeding the surface loses

its roughness and the skid resistance becomes very low. It looks very similar to bleeding but is only in the wheel paths. Fatting up is also known as tracking that can be caused by channelized traffic. The reason for tracking can sometimes be due to bleeding or because of bad design of surface dressing e.g. wrong aggregate size or the surface dressing does not work in the environmental conditions when paved. [27]

Defect when mosaic is disrupted are: scabbing, tearing, fretting or streaking. [47] Scabbing is when either bitumen or aggregate are lost from the surface dressing after paving. Often the reason is that oil, dust or dirt was in the substrate. This can also happen if the substrate is wet or cold during paving causing no adhesion between the bitumen to the layer. Fretting is when interstitial fines from the road surface are progressively lost. It usually happens where there is too little bitumen content so it does not adhere to the aggregates or if there is water between the aggregates and bitumen. If the road surface where the fines are lost are bigger than 0.01 m^2 (100x100 mm) it is not called fretting but tearing. Tearing is common in places where roads are under a lot of strain due to intersections or turns. Streaking is when there are stripes in the asphalt where aggregates did not adhere to the bitumen. This is mainly due to too little bitumen because of uneven application of the emulsion. [27] Another defect is rutting that is where surface depression is in the wheel path. Along sides of the rut there can occur pavement uplift. It can happen due to pavement deformation e.g. because of insufficient compaction of pavement layers during construction. Furthermore it can also happen due to mechanical dislodging because of studded tires. Ruts can be dangerous when it rains, then they are filled with water and pull a vehicle to the rut path as it is steered across the rut. [50]

7.3 Aggregates in surface dressing
Aggregate for surface dressing can be natural, manufactured or recycled. [51] The aggregates should consist of crushed stone, crushed gravel (shingle) or other crushed aggregates, uncrushed aggregates should not be used. Furthermore its properties should be clean, strong, durable and mostly free from

dust and adherent coatings. It is better if the aggregates are hydrophobic in nature and have low porosity. [45]

It is okay to use damp aggregates for surface dressing with cationic bitumen emulsion and therefore if the aggregates are dusty they should be cleaned by washing them with water, either by dipping or sprinkling. [45] However it must be taken into consideration that the aggregates have worse adhesion if they are moist. [29]

The size of the aggregate is taken into consideration when listing qualities that they must have to be used for surface dressing with emulsion. The values are dependent on circumstances at each site, however other qualities that are required are i.e. resistance to fragmentation, resistance to polishing, satisfactory shape and resistance to abrasion [52]

Almost all types of aggregates have similar skid resistance when the surface is freshly laid. However it differs how fast they polish due to traffic, which reduces the resistance to skidding. Furthermore satisfactory shape is important for surface dressing due to after rolling and compaction by traffic some individual chippings will be inclined to lie on their longest dimension and flaky chippings do not stand above the binder film as much as more cubically shaped chippings. It is also important to have aggregates in the right shape to get good embedment into the road surface. [52]

8. Iceland

8.1 Climate

Iceland is located close to the border between warm and cold ocean currents. The Gulf Stream flows along the south and western part of the island that greatly moderates the climate. Meanwhile the East Greenland Current flows west of Iceland while a branch of it called the East Icelandic Current approaches the northeast- and east coast of the country. [53, 54] These currents have great

influence on weather and climate both by coast but also because all air masses get to Iceland after having passed over the sea. Cyclones are frequent in the vicinity of Iceland that affects the weather greatly, at particular time the weather type is different from one part of the country to another due to wind direction and topography. The climate in Iceland is maritime and therefore the air humidity is comparatively high with a monthly mean relative humidity usually between 75-90%. In Iceland there are cool summers and mild winters where the annual mean temperature ranges from 2.0°C to 5.7°C in the lowlands. [53] The mean temperature in January in the coastal lowlands is close to 0°C and in July the average temperature exceeds 10°C in the lowlands of south and west of Iceland but lower than that in other parts of the country. [54] Frost is frequent in Iceland but winter thaws are common and therefore the frost normally does not last long. Moreover thaws are the distinctive characteristic of Icelandic weather. Great part of precipitation in Iceland falls with winds between east and south that is carried in the forward part of cyclones coming from the southwest. Precipitation depends a lot on local conditions and can vary greatly within a short distance. The estimated maximum annual value in the southeast is more than 4,000 mm while in the southwestern and western Iceland the amount in the lowlands is 1,000-1,600. The lowest value is in an extensive area north of Vatnajökull, where it creates a rain shadow, with less than 400 mm. In the north of Iceland more than half of the winter precipitation falls as snow and a complete snow cover may remain for weeks or even months. However in the southern Iceland the snow cover is more variable. Winter thaws are frequent and can alter the snow cover particularly in the south where rain usually accompanies the thaws. However it is difficult to classify precipitation as rain or snow because a part of precipitation is mixed of both types. [53]

Another distinctive characteristic of Iceland is due to geographical position the day is very long during the summer and short during the winter. In Reykjavik, which is in the southwest of Iceland, the time from sunrise to sunset is 21 hours and 9 minutes on midsummer (21. June) while the shortest day is 4 hours and 8

minutes. In the north part of Iceland, Akureyri, the times between sunrise and sunset are 24 hours for the longest day and 3 hours and 6 minutes for the shortest day. [55]

8.2 Emulsion in Iceland

In Iceland there are only used two types of bitumen that is bitumen with penetration 160/220 and 70/100. For bitumen emulsion there is usually used 160/220 with approximately 70% bitumen content. This is important because of porosity of aggregates, cold weather and to decrease the possibility of water damage. [12] The surface dressing results have been inconsistent for the last few years. There is often deformation in the roads after the winter however there is a constant change in the recipe of the emulsion trying to make it better for the Icelandic climate. [56]

For the last couple of years fluxed bitumen has been mostly used however cutback bitumen is still used in a small amount, but in earlier years it was used a lot more. [27] Both bitumen products have reduced viscosity but their difference is that for cutback there has been an addition of a volatile cut-back solvent e.g. white spirit or kerosene while in fluxed bitumen there has been added non-volatile fluid (oil) that makes the bitumen softer without intensifying the volatility. [3] In Iceland the non-volatile oil used is 5.5-6.5% ethylester from fish oil (depending on temperature and conditions) and 0.9% adhesive agent. [27] However there have been experiments with bitumen emulsions and for the last few years the use of cationic bitumen emulsion has been increasing and it can be expected that they will be used even more in coming years. [27] The emulsion recipe in Iceland always contains calcium chloride, hydrogen chloride, bitumen and water with addition of different emulsifiers. Polymer modified surface dressing has also been tested by adding latex. [56]

In Iceland surface dressings are paved from June to August depending if the weather is favorable so adhesion can be accomplished between binder and

aggregate. Bitumen emulsion is especially sensitive to low temperatures and therefore it should be paved in the middle of the summer at good conditions. Even though surface dressing looks like it has been paved well late in the season it has to be considered that the durability can be insecure. If it is getting late in the paving season it should be considered to use racked-in surface dressing. However it should be avoided to pave bitumen emulsion late in the season, especially on roads with heavy traffic due to fretting. [27]

8.3 Aggregates in Iceland

The most common type of rock in Iceland is basalt and it is divided into many subtypes. Basalt can also be categorized depending on its properties for asphalt, that is depending on e.g. alteration and porosity that affects the strength, weathering tolerance and wear tolerance of the rock. [57]

In Iceland the main type of aggregate used for road construction is basaltic rock. Iceland is situated at divergent plate boundaries and due to that has active volcanism and the majority are basaltic extrusive rocks. The oldest basalts in Iceland are around 15 million years old and therefore the source of magma is basic and primitive where it is originated in the mantle of the earth. Basaltic origin is around 80-90% of Icelandic bedrock. However in places where volcanism has been active there can be found acidic rocks, mainly rhyolite and granophyres. Hydrothermal processes have usually caused very altered basalts in such areas. [58]

Here the term basaltic aggregate is used in an engineering context from the British Standard specification (BS 812). Where Basalt Group includes andesite, basalt basic porphyrite, diabase, dolerite, lamprophyre, quartz-dolerite and spilite i.e. a range of volcanic rocks of basic composition and fine to medium grained of intermediate. [58]

By using simplified petrography basalts in Iceland, they are classified mostly by porosity (dense, porous or very porous) and alteration (fresh, altered or very altered). Other factors observed are e.g. shape and cleanliness. However petrological types e.g. scoria, pyroclastic and pumice are not classified as basalt in this way. [58]

For hot mix asphalt, aggregates have been imported from Norway to use on roads with more than 8000 AADT. The imported aggregates are a type of quartz diorite (porphyrite). This is very expensive and transferring the aggregates between countries and then by trucks in Iceland both costs a lot of money and it is not good for the environment. Around 2/3 of the price for the Norwegian aggregates is freight cost and it can be up to double the price for Icelandic aggregate. However this can vary, depending on where the quarries and the ports are. The average cost of Icelandic aggregates are 20 euro/ton compared to the Norwegian ones, which are around 40 euro/ton before tax. [56, 59]

8.4 Challenges

As previously mentioned the summers in Iceland are cool with addition of rainy days and therefore the time to layout surface dressing is not long. Furthermore due to long sun hours in the summer the road temperature can be very high even though the air temperature is relatively low. This has caused some issues where the emulsion does not break when it is laid out. Another possible issue is the high humidity that causes it to take longer time for the emulsion to cure. As previously mentioned the asphalt is deformed in the first 12 months, if it looks good after that time it will last. The surface dressing in Iceland usually looks good in the end of August but then after facing the elements of winter, it often deformed. That is due to many freeze thaw cycles and increasing the deformation of the roads even more are studded tires, snow plough and salt. [56] Due to these environmental conditions in Iceland (freeze-thaw fluctuations, wet wearing surface due to precipitation and thaw of ice) there are great demands on the adhesion of bitumen emulsion with the aggregate. [12]

9. Experiments

For performance of the asphalt, wetting of the bitumen is very important. The most direct way to measure adhesion strength between aggregate and the binder is to determine the wetting contact angle. However this is very hard to measure due to high viscosity of the bitumen. Aggregate surfaces also contain areas of various minerals and the wettability will not be the same for each mineral. Therefore to characterize bitumen wetting angle over the aggregate surface is not very favorable. Hence, it was decided to use practical measurement. [28]

9.1 Materials

9.1.1 Aggregates

Swedish granite from Skanska Södertälje in size 8-11 and Icelandic basalt from Hólabrú in size 5-11 was used.

Figure 23: Picture of the aggregates used for the experiment, granite on the left and basalt on the right

In the EN 13043 standard it is recommended that the fines content is f1, i.e. should not be more than 1% passing 0.063 mm sieve. However some contactors may require less fines, content f0.5, i.e. no more than 0.5% pass the sieve. [52]

Figure 24: Gradation of the Swedish granite.
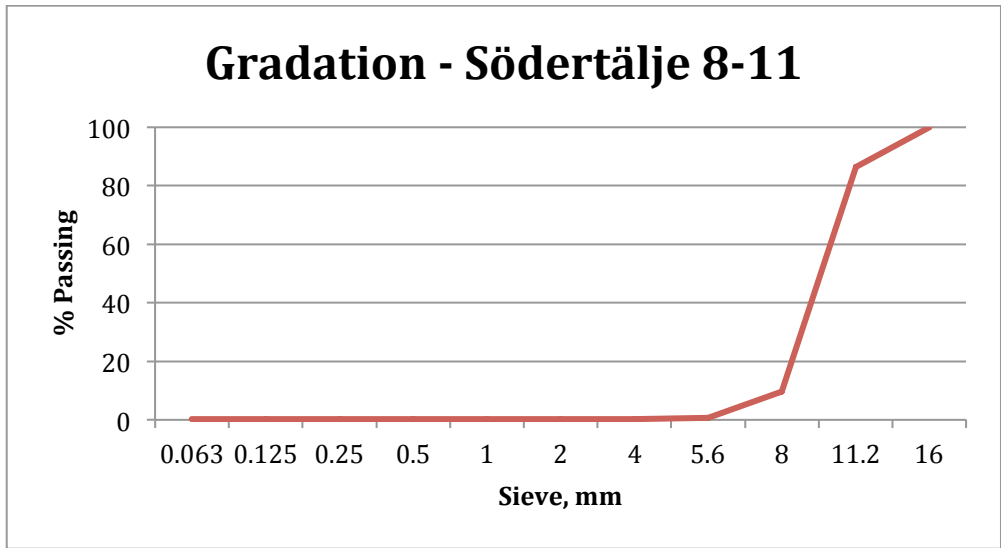
On Figure 24 is a graph of the gradation of the Swedish granite. It is uniformly graded where only 0.2% passed the 0.063 mm and so the fines are below the limits of the standard.
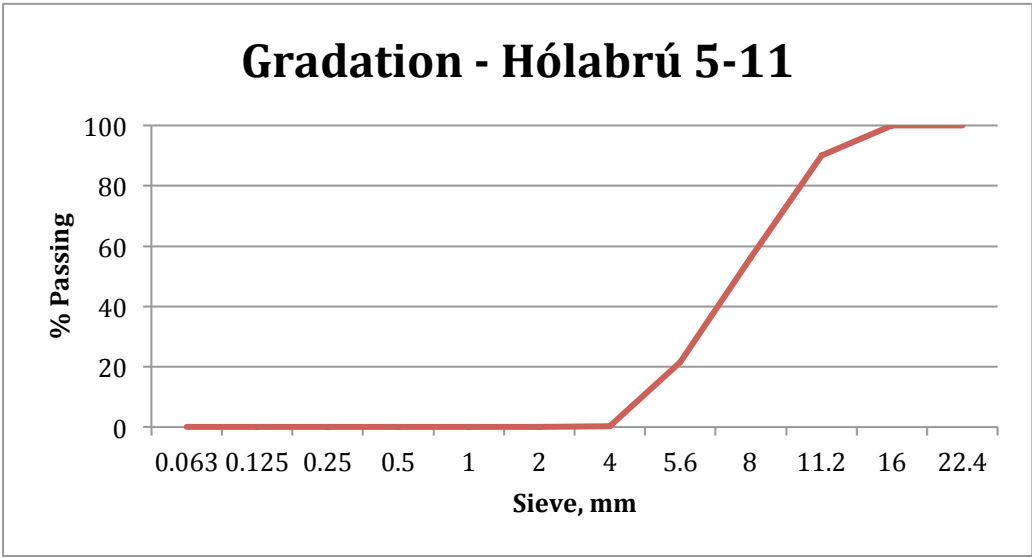

Figure 25: Gradation of the Icelandic basalt.

On Figure 25 there is gradation graph for the Icelandic basalt. It is uniformly graded as well and 0% passed the 0.063 mm, so there are no fines.

9.1.2 Emulsion

In this experiment C69B2 emulsion with bitumen of 160/220 penetration grade was used. It is a common surface dressing used in Sweden produced by Nynas. Further information about the emulsion can be found in Table 3.

Table 3: Properties of the bitumen emulsion used for the experiment.

Test	Method SS-EN	Unit	Results
Binder content	1428 1431	Weight %	67
Efflux time [4mm 50°C]	12846	Seconds	38
Breaking value	13075-1	-	63

9.2 Experimental

The Vialit shock plate method evaluates adhesion performance qualitatively between aggregate and emulsion and has been standardized in (SS-EN) 12272-3. [1, 60] The first step of the procedure was to take the aggregates and put them in a refrigerator at 6°C for 24 hours. Then the samples were prepared by pouring 60g of bitumen emulsion at 60°C was spread evenly on 20 cm x 20 cm steel plates. After the emulsion is spread on the plates it was put in a refrigerator at 6°C in 20 minutes and then it was taken out and 100 chippings spread evenly over the whole plate. Afterwards it was placed in a ventilated climatic chamber at room temperature until it achieved constant mass. This took approximately 24 hours. Then the plates were put in a refrigerator again at 6°C for 20 minutes. Finally the plates were placed on an apparatus which is made of rigid base with 3-pointed supports including a vertical support ending in a lightly angled slide as can be seen on

Figure 26. Then a steel ball of mass 510 g was dropped three times within 10 seconds from the angled slide. After the third drop the plate was examined and number of chippings that had fallen were counted.
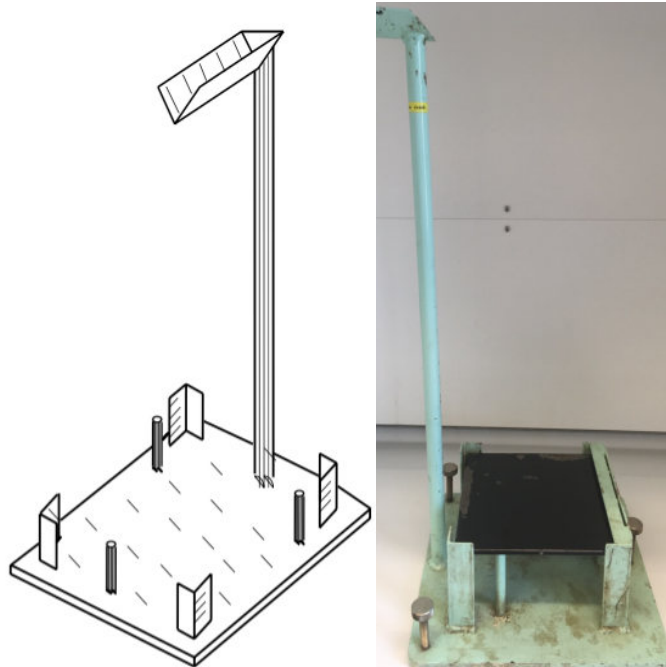

Figure 26: Schematic picture of the apparatus used [61] and a picture of the set up of the experiment.

9.3 Results and discussion

During the Swedish summer the temperature is higher than in Iceland while the winters are colder. Just like Iceland, snow covers are common, especially in the north, with most of the country icebound in winter except maybe in the south. [62] The humidity in Sweden in the summer is high, with 75-90% in the south while in the north it is between 75-85%.[63] Furthermore the north of Sweden also has continuous daylight during summer however this does not happen in the south of Sweden with "only" 19 hours of daylight in midsummer. [62] Therefore it is possible to say that the climate in Iceland and north of Sweden is similar with long days, high humidity in the summer, snow and cold summers, where in Iceland the average temperature in the summer is between 10-12°C but in the north of Sweden it is between 12-13°C. [64, 65] However the freeze-thaw cycles are more common in Iceland than in the north of Sweden. [66]

Because of the similar climate it was considered interesting to use a well known emulsion from Sweden. The emulsion used for the experiment has been used by Nynas for a long time and is used all over the country. This recipe of bitumen emulsion mixed with the aggregates used in Sweden has shown great qualities. Therefore it is considered unnecessary to test the performance of the emulsion with the aggregate annually.

However as previously mentioned the Icelandic basalt has been causing troubles in Iceland for a long time. A decision has been taken to stop using it for hot mix asphalt and therefore the cost of paving roads has increased. If Swedish granite would be imported to use with the surface dressing instead of the Icelandic basalt it would be approximately double the price, similar to the price of the Norwegian aggregates.

The aggregate size differs where the granite was 8-11 while the basalt was in size 5-11. This is due to the 5-11 basalt is used as 8-11 in Iceland. [66]

Figure 27: Samples G1 and G2 before curing.

Table 4: Results from the Vialit shock plate experiment.

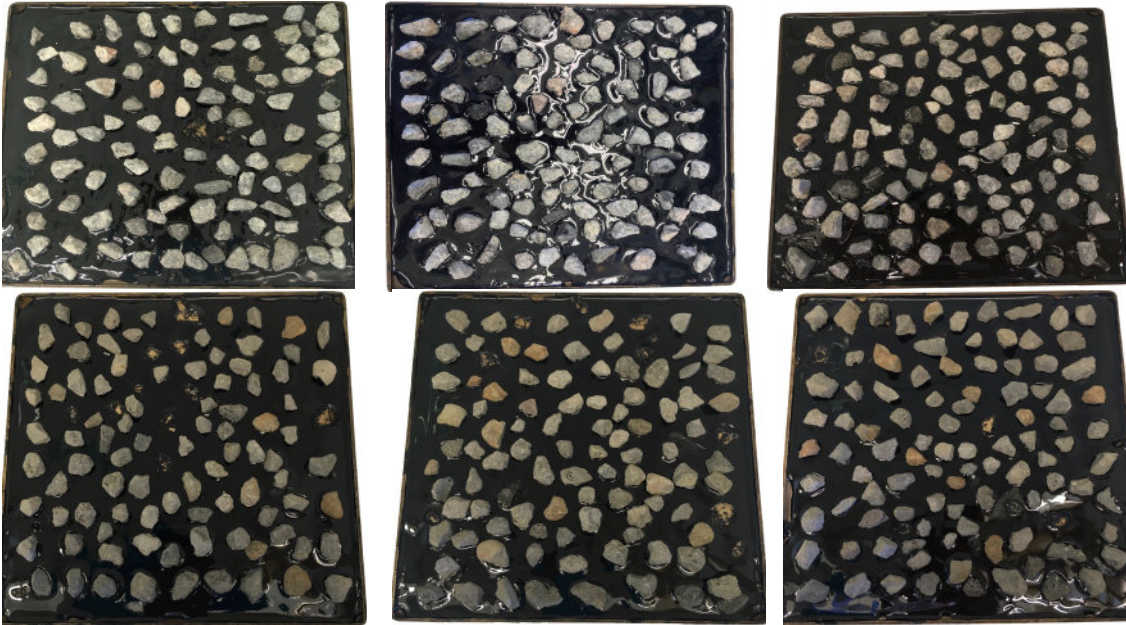| Sample	Fallen aggregates	Mean value
G1	2	
G2	0	0.7
G3	0	
B1	10	
B2	9	7.7
B3	4	

Figure 28: The samples after the experiment. Granite is in the upper row: G1-G2-G3 and basalt in the lower: B1-B2-B3.

The main purpose of this experiment was to see how well the basalt would do compared to the granite. As can be seen in Table 6 the granite only loses approximately 0.7 aggregates while the basalt looses 7.7 aggregates. This indicates that the adhesion between the granite and the emulsion is better than between the basalt and the emulsion. The adhesion for the basalt is not bad, however there is a difference between the two. Hence, it would not be preferable to use this emulsion with basalt in Iceland in practice, right now.

Further experiments should be conducted to evaluate better how the bitumen emulsion works with the basalt. Examples of experiments are e.g. test the zeta potential of the emulsion and aggregate separately and to use wheel tracking device to see prediction of rutting, fatigue, moisture, susceptibility and stripping of the asphalt mixture. Furthermore as a further experiment rolling bottle test can also be conducted to determine the affinity between the basalt and the emulsion.

As mentioned previously there have been problems using the Icelandic basalt and in a study by Khan [22] four different aggregates were tested with three different binders i.e. bitumen 70/100, bitumen 70/100 mixed with emulsifier Redicote EM44 and bitumen 70/100 mixed with adhesion promoter Wet Fix. The aggregates were three different granite and Icelandic basalt. This study showed that the adhesion was always stronger between the binder and the granite rather than with the basalt. In the study the aggregates were both tested dry and wet, and for all aggregates it was better for them to be dry. When comparing the dry-wet ratio between the aggregates basalt has the highest ratio, which means it is more important for the basalt to be dry. [22]

For future work it would be interesting to change the recipe of the bitumen emulsion a little bit to see what affects the adhesion the most by changing the amount of calcium chloride and emulsifier for example. It would also be curious to try other known bitumen emulsion to see if they work better with the basalt. Furthermore to try the basalt with polymer modified emulsion would be interesting and perform the Vialit shock plate method. That is, until an emulsion is found that works as well for the basalt as the emulsion, used in this experiment, worked with the Swedish granite.

10. Conclusion

Surface dressing is a very interesting possibility for road construction because it is both economical and environmentally friendly with lower emissions compared

to hot mix asphalt. The surface dressing is made of aggregates and emulsion. The emulsion is produced by using mechanical energy to break down bitumen into droplets and mix it with soap solution that contains water, emulsifier and additives. The breaking and setting process of the emulsion is not perfectly understood but there are theories on how it works. The emulsion starts to break by flocculation that leads to coalescence and finally the emulsion has settled or cured when all the water has been absorbed or evaporated. The properties that must be looked at when picking aggregates for asphalt are e.g. cleanliness, size and grading. This is important for example due to the adhesion between the aggregates and the emulsion, which is very important to have to make long lasting roads. One possible application of bitumen emulsion is called surface dressing. It is an interesting technique due to it is relatively cheap and it is possible to pave many square meters each day. If the construction of the road is not good enough the surface dressing will have defects. Either where binder covers the aggregates e.g. bleeding or where the aggregates are disrupted e.g. tearing and fretting. There has been an increase in the last few years to use surface dressing in Iceland. However, there are many challenges that have to be overcome when using it. The climate is difficult with cold summers, precipitation, high humidity and many freeze-thaw cycles. Furthermore snow covers and everything that follows: snow plough, salt and studded tires causes great deformation of the roads. Furthermore the long days in the summer with up to 24 hour sunshine has also caused troubles when paving. There have also been challenges in using the basalt for road construction and therefore aggregates are imported from Norway to use with hot mix asphalt. This is however a very expensive procedure and therefore it is still in interest of using basalt for surface dressing. Therefore the experiment performed was to see how the Icelandic basalt would perform on an adhesion test compared to Swedish granite by using the same emulsion. The goal was to hopefully be able to use the emulsion recipe in Iceland. However after performing the Vialit shock plate method it was clear that the basalt was not as good as the granite and therefore it is not seen preferable to use the emulsion in practice in Iceland right now. However further

research on the emulsion with the basalt has to be conducted by e.g. performing rolling bottle test and testing the zeta potential of both the emulsion and basalt. Future work would be to try other recipes of bitumen emulsions e.g. by changing the C69B2 from Nynas a little bit to see what affects the adhesion the most with the basalt. With the goal to find emulsion that works as well with the basalt as the emulsion, that was used in this experiment, works with the Swedish granite.

11. References

1.	Swedish Standard Institute, *Surface dressing - Test method*, in *Part 3: Determination of binder aggregate adhesivity by the Vialit plate shock test method*. 2003.
2.	Sjöblom, J., *Emulsions and Emulsion Stability: 2nd ed.* Surfactant Science Series, 132. 2006: Boca Raton: Taylor & Francis.
3.	Asphalt Institute and European Bitumen Association, *The Bitumen Industry - a Global Perspective: Production, Chemistry, Use, Specification and Occupational Exposure*. Vol. Third edition. 2015.
4.	Bitumina. *Bitumen Crude: Understanding Bitumen Feedstock & Technology*. 2014 [cited 2018 26. March]; Available from: http://www.bitumina.co.uk/bitumen-crude.html.
5.	Rudyk, S., *Relationships between SARA fractions of conventional oil, heavy oil, natural bitumen and residues.* Fuel, 2018. **216**: p. 330-340.
6.	Needham, D., *Developments in bitumen emulsion mixtures for roads*, in *Department of Civil Engineering*. 1996, University of Nottingham.
7.	Santos, R., et al., *An overview of heavy oil properties and its recovery and transportation methods.* Brazilian Journal of Chemical Engineering, 2014. **31**(3): p. 571-590.
8.	Morán, Y.L., *Integrated processing for heavy crude oil*, in *Engineering and Physical Sciences*. 2014, The University of Manchester.
9.	Meyer, R.F., E.D. Attanasi, and P.A. Freeman, *Heavy oil and natural bitumen resources in geological basins of the world*. 2007: Reston, Virgina.
10.	Singh, H. and P.K. Jain, *Bitumen quality and manufacturing processes-Past and present technological status.* 1997.
11.	Robinson, H.L., *Polymers in Asphalt*. Smithers Rapra Technology. p. 14-29.
12.	Jóhannesson, Á., *Ítarefni um malbik*. 2008.
13.	Rubio, M.d.C., et al., *Comparative analysis of emissions from the manufacture and use of hot and half-warm mix asphalt.* Journal of Cleaner Production, 2013. **41**: p. 1-6.
14.	Rubio, M.C., et al., *Warm mix asphalt: an overview.* Journal of Cleaner Production, 2012. **24**: p. 76-84.
15.	Kristjánsdóttir, Ó., *Warm mix asphalt for cold weather paving*. 2006, University of Washington Seattle.
16.	Vaitkus, A., et al., *Analysis and evaluation of possibilities for the use of Warm mix asphalt in Lithuania*. Vol. 4. 2009. 80-86.
17.	Vaitkus, A., V. Vorobjovas, and L. Žiliūtė, *The research on the use of warm mix asphalt for asphalt Pavement structures*. 2009.
18.	Bueche, N. *Warm asphalt bituminous mixtures with regards to energy, emissions and performance*. in *Proceedings of the Young Researchers Seminar*. 2009. Torino, Italy.
19.	Larsen, O., *Warm Asphalt Mix with Foam–WAM Foam*, in *IRF*. 2001, Partie B Thèmes Techniques S.00469: Norway.

20. Chowdhury, A. and J.W. Button, *A review of warm mix asphalt*. 2008, Transporation Institue, the Texas A & M University System.
21. NAPA. *History of Asphalt*. [cited 2018 29. March]; Available from: http://www.asphaltpavement.org/index.php?option=com_content&view=article&id=21&Itemid=268.
22. EAPA. *The Use of Bitumen Emulsion In Europe*. [cited 2018 29. March]; Available from: http://www.eapa.org/publications.php?c=73.
23. Colas Solutions Inc. *The Colas Group*. [cited 2018 30. March]; Available from: https://colassolutions.com/the-colas-group/.
24. James, A., *Overview of asphalt emulsion.* Transportation research circular, 2006: p. 1-15.
25. Dybalski, J.N., *The Chemistry of Asphalt Emulsions: Fifty-fifth Annual Meeting*. 1976: Transportation Research Board.
26. Khan, A., P. Redelius, and N. Kringos, *Investigating effects of salts on the coalescence process in bitumen emulsions.* 2018.
27. Bjarnason, G. and P. Pétursson, *Handbók um klæðningar*. Vol. 1. 2017.
28. Khan, A., *Fundamental investigation to improve the quality of cold mix asphalt*, in *TRITA-BKN. Bulletin*. 2016, KTH Royal Institute of Technology: Stockholm. p. 59.
29. Khan, A., P. Redelius, and N. Kringos, *Towards understanding the breaking and coalescence of bitumen emulsions for cold asphalt*. 2016.
30. Banerjee, A., *Breaking and curing rates in asphalt emulsions*, in *Civil, Architectural and Environmental Engineering*. 2012, The University of Texas at Austin.
31. Gaestel, C., *The Breaking Mechanism of Cationic Bitumen Emulsions.* Sci Road and Bulding Material Group, 1967: p. 221-224.
32. Wates, J.M. and A.D. James, *Zeta-potential measurements on bitumen emulsion and road aggregates*. 1993, Paris: First World Congress on Emulsion.
33. Plotnikova, I.A., *Control of the interaction process between emulsion and mineral aggregate by means of physico-chemical modification of their surfaces*. 1993, Paris: First Wold Congress on Emulsion.
34. Baumgardner, G., *Overview of Asphalt Emulsion.* Asphalt Emulsion Technology, 2006: p. 16-20.
35. Kulkarni, V.S., *Handbook of Non-Invasive Drug Delivery Systems - Non-Invasive and Minimally-Invasive Drug Delivery Systems for Pharmaceutical and Personal Care Products*. Elsevier. p. 66-67.
36. Cui, S., et al., *Durability of asphalt mixtures: Effect of aggregate type and adhesion promoters.* International Journal of Adhesion and Adhesives, 2014. **54**: p. 100-111.
37. Svergies geologiska undersökning. *Geology of Sweden*. [cited 2018 3. May]; Available from: https://www.sgu.se/en/geology-of-sweden/.
38. Steinþórsson, S. *Eru til sérstakir íslenskir steinar?* 2002 [cited 2018 3. May]; Available from: https://www.visindavefur.is/svar.php?id=2298.
39. APAI, *Asphalt Paving Design Guide*. Iowa.

40.   Jóhannesson, Á., et al., *Notkun bergs til vegagerðar. Vinnsla, efniskröfur og útlögn.* 2010.

41.   Moraes, R., R. Velasquez, and H. Bahia, *Measuring the effect of moisture on asphalt-aggregate bond with the bitumen bond strength test.* Transportation Research Record: Journal of the Transportation Research Board, 2011(2209): p. 70-81.

42.   Paliukaitė, M., et al., *Evaluation of Different Test Methods for Bitumen Adhesion Properties.* Transportation Research Procedia, 2016. **14**: p. 724-731.

43.   Grenfell, J., et al., *Assessing asphalt mixture moisture susceptibility through intrinsic adhesion, bitumen stripping and mechanical damage.* Road Materials and Pavement Design, 2014. **15**(1): p. 131-152.

44.   Caro, S., et al., *Moisture susceptibility of asphalt mixtures, Part 1: mechanisms.* International Journal of Pavement Engineering, 2008. **9**(2): p. 81-98.

45.   The Indian Roads Congress, *Standard Specifications and Code of Practice for Design and Construction of Surface Dressing*, in *110-2005*. 2005: New Delhi.

46.   Jenny-Ann Östlund, *Personal communication*. 27. April 2018.

47.   Swedish Standard Institute, *Vägmaterial - Ytbehandling- Krav. Surface dressing - Requirements*, in *SS-EN 12271:2006*. 2006.

48.   Hunter, R.N., *Asphalts in Road Construction*. 2000: Thomas Telford.

49.   Nicholls, J.C., *Asphalt Surfacings: A Guide to Asphalt Surfacings and Treatments Used for the Surface Course of Road Pavements*. 2002, London and New York: Taylor & Francis.

50.   Erlingsson, S. *Failure Modes in Pavements*. 2013 [cited 2018 17. May]; Available from: https://www.kth.se/social/upload/5149e50df27654634ecd1034/Pavement.

51.   Staðlaráð Íslands, *Aggregates for bituminous mixtures and surface treatment for roads, airfields and other trafficked areas*, in *ÍST EN 13043:2002*. 2002.

52.   Road Surface Treatments Association. *Note on Surface Dressing Aggregates*. 2014 [cited 2018 10. April]; Available from: https://www.rsta-uk.org/downloads/RSTA-ADEPT-Code-of-Practice-for-Surface-Dressing-Pt3-Aggregates-2014.pdf.

53.   Einarsson, M.Á., *Climate of Iceland*, in *World Survey of Climatology: 15: Climates of the Oceans*, H. van Loon, Editor. 1984, Elsevier: Amsterdam. p. 673-697.

54.   Ingólfsson, Ó. *The Dynamic Climate of Iceland*. 2008 [cited 2018 7. May]; Available from: https://notendur.hi.is/oi/climate_in_iceland.htm.

55.   Sæmundsson, Þ. *Sólargangstöflur*. 2018 [cited 2018 2. May]; Available from: http://www.almanak.hi.is/solgang.html.

56.   Sigþór Sigurðsson, Sigurður Benediktsson, and Gísli Eymarsson, *Personal communication*. 27. April 2018.

57.   Jóhannesson, Á., et al., *Sprengt berg í vegagerð. Handbók fyrir vegagerðarmenn*. 2012, Ísland: Vegagerðin.

58. Pétursson, P., et al., *Comparison of Basaltic Aggregates from Iceland, West Java and Northern Ireland*. Vegagerdin.

59. Malbikunarstöðin Hlaðbær Colas. *Durasplitt*. [cited 2018 9. May]; Available from: http://www.colas.is/vorur/malbik/durasplitt/.

60. Yi, J.Y., et al., *Investigation on Adhesive Behavior between Binder and Aggregate by Vialit Test under Low Temperature.* Advanced Materials Research, 2013. **723**: p. 389-396.

61. California Department of Transportation. *Vialit Test for Aggregate Retention in Chip Seals*. Available from: http://www.dot.ca.gov/ctm/pdf/Vialit_Test.pdf.

62. Swedish Institute. *The Swedish climate*. 2018 [cited 2018 4. May]; Available from: https://sweden.se/nature/swedish-climate/.

63. SMHI. *Luftfuktighet*. 2017 [cited 2018 4. May]; Available from: https://www.smhi.se/kunskapsbanken/meteorologi/luftfuktighet-1.3910.

64. SMHI. *Temperatur*. 2014 [cited 2018 4. May]; Available from: https://www.smhi.se/kunskapsbanken/meteorologi/temperatur-1.3843.

65. Veðurstofa Íslands. *Tímaraðir fyrir valdar veðurstöðvar*. [cited 2018 4. May]; Available from: http://www.vedur.is/vedur/vedurfar/medaltalstoflur/.

66. Sarady, M. and E.A. Sahlin, *The influence of snow cover on ground freeze-thaw frequency, intensity, and duration: An experimental study conducted in coastal northern Sweden.* Norsk Geografisk Tidsskrift-Norwegian Journal of Geography, 2016. **70**(2): p. 82-94.