Steffen Bech Stene

Investigation of causes to blistering of asphalt pavements

Masteroppgave i Veg, jernbane, transport og geomatikk
Veileder: Inge Hoff
Juni 2020

Masteroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for bygg- og miljøteknikk

Kunnskap for en bedre verden

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Forord

Denne masteroppgaven er utført ved Norges teknisk- naturvitenskapelige universitet på institutt for bygg- og miljøteknikk. Oppgaven er en del av spesialisering innen veg-teknologi, og består av en vitenskapelig artikkel med vedlegg.

Jeg ønsker å takke min veileder, professor Inge Hoff, for god veiledning og gode ideer til stor hjelp i prosjektet. Samtidig vil jeg takke Ph.d. Sara Anastasio i Forsvarsbygg, for idé til problemstilling, mye god hjelp underveis, og for tilrettelegging av befaringer. Sist, men ikke minst ønsker jeg å takke de ansatte på vegteknologisk laboratorium ved NTNU som har hjulpet meg mye i starten av laboratoriearbeidet. Det har vært svært lærerikt og interessant å få jobbe med asfaltmaterialer i laboratoriet, og erfaringer fra dette har bidratt til at jeg fått en mye bedre forståelse for fagfeltet.

Underveis i arbeidet med denne masteroppgaven ble viruset SARS-Cov-2 spredt til Norge, og flere tiltak for å hindre videre smitte av viruset ble iverksatt i det norske samfunnet. Dette medførte at felt og laboratoriearbeid ikke kunne gjennomføres som planlagt, og det påvirket tidsbruken og metodene i oppgaven. Utdypende informasjon om dette ligger vedlagt.

Trondheim, 21. Juni 2020

Steffen B. Stene

Steffen Bech Stene

Sammendrag

Gjennom årene er det blitt foreslått flere hypoteser om årsakene til blemmer i asfaltdekker. Den vanligste oppfatningen har vært at det oppstår en vann- og/eller gassfylt lomme mellom de øvre asfaltlagene, eller i selve asfaltlaget. Når dekket varmes opp av solen på varme sommerdager oppstår blemmene på grunn av luftekspansjon og damptrykk. Blemmer i asfaltdekket fører til utilfredsstillende jevnhet, og kan skape strekkspenninger som forårsaker oppsprekking. Etter hvert kan sprekker i dekket utvikle seg til slaghull. Løse asfaltpartikler som produseres i denne prosessen representerer en risiko for flysikkerheten ved blemmeproblematikk i asfalterte taxi- og rullebaner på flyplasser.

Denne studien har undersøkt årsakene og mekanismene til formasjonen av blemmer, og ble initiert på grunn av økende forekomst av fenomenet ved norske flyplasser og veger. Studien har fokusert på en grundig gjennomgang av teorien om luftekspansjon og damptrykk som årsak til blemmene. Det er også gjennomført forsøk med formål å gjenskape blemmer i laboratorieproduserte asfaltplater, i tillegg til diskusjon av foreløpige undersøkelser og observasjoner av blemmeforekomster på norske veger og flyplasser.

Resultater fra forsøket indikerer at blemmer kan oppstå selv ved relativt lave trykk og temperaturer. Den tids- og temperaturavhengige viskøse deformasjonsresponsen i asfaltmaterialer gjør at sakte genererte trykk fra luftekspansjon og damptrykk over tid kan skape blemmer i asfaltdekket. For at blemmene skal oppstå på grunn av oppvarming gjennom solstråling, må asfaltdekket være praktisk talt impermeabelt for vanndamp, og volumet av luft og fuktighet fanget under asfaltdekket må være tilstrekkelig. Egenskaper og/eller skader i underliggende asfaltlag som gjør at et større volum av luft og fuktighet er fanget under dekket kan derfor muligens øke risikoen for blemmer.

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Investigation of causes to blistering of asphalt pavements

Steffen Bech Stene*

Abstract

Over the years, several hypotheses have been proposed for the causes of blistering in asphalt pavement surface layers. The most common perception is that a water and/or gas-filled pocket is created in between the different asphalt layers, or in the asphalt layer itself. When subjected to solar radiation the blisters grow because of air expansion and vapor pressure. Blisters in the pavement surface layer leads to unsatisfactory evenness and can create tensile stresses that cause cracking. Eventually, cracks in the overlay can develop into potholes. Loose asphalt particles produced during this process represent a risk to air traffic safety in case of blistering problems in paved taxiways and runways at airports.

This study, investigating the causes and mechanisms for blistering was initiated because of increasing occurance of the phenomenon at Norwegian airports and roads. It has focused on a thorough review of the theory of air expansion and vapor pressure as the cause of the blistering. In addition, a experiment has been carried out with the aim of recreating blisters in laboratory-produced asphalt concrete slabs.

Results from the experiment indicate that blisters can occur even at relatively low pressures and temperatures. The time- and temperature dependent viscous stress response in asphalt materials, means that slowly generated pressures by air expansion and vapor pressure can over time create blisters in the asphalt concrete overlay. In order for the blisters to arise because of solar radiation, the asphalt concrete surface layer must be practically impermeable to water vapor, and the volume of trapped air and moisture below the surface layer must be sufficient. Properties and/or damages to subsurface layers that allow a greater volume of air and moisture to be trapped underneath the overlay may therefore increase the risk of blistering.

Keywords
Asphalt pavement blistering, Air expansion, Vapor pressure, Blister experiment

* This paper was authored by Steffen Bech Stene with Professor Inge Hoff and PhD Sara Anastasio as advisors, potential future submissions of this paper will be with Steffen Bech Stene, Professor Inge Hoff, and PhD Sara Anastasio as authors.

1 Introduction

Blistering in asphalt pavements is when parts of the overlay is separated from the subsurface layer because of an upheaving gas pressure. Blisters with diameters up to about 100 cm have been observed forming and they can often protrude several cm from the surface. When blisters occur, it leads to unsatisfactory evenness of the pavement, and it can further lead to weaknesses and tensile cracks that eventually develop into a pothole. Loose asphalt particles that are produced during this process are especially a concern for air traffic safety at airports, often referred to as FOD's (foreign object debris). Runway and taxiway FOD's such as asphalt particles can cause severity and destruction to the aircraft such as engine failure, and this can lead to loss of human life as the ultimate consequence (Hussin, Ismail and Mustapa, 2016). On roads the blisters can provide an uncomfortable ride and represent a hazard for motorcyclists. They also increase the possibility for more serious damage to the pavement during mechanical removal of snow (Hovin, 2018). The development of cracks, potholes and unevenness will also often lead to a shorter lifetime of the pavement surface layer.

Over the years several hypotheses have been proposed for the cause of blistering. Croll (2008) suggested a solution that states that thermal expansion and contraction in the pavement overlay due to temperature fluctuations, cause a ratchet effect that over time causes them to grow.

Gas-producing biological and chemical activity as the main cause has also been suggested and investigated. Hironaka and Holland (1986) conducted a comprehensive investigation of asphalt pavement blisters on a military airport in Beaufort South Carolina, USA. Through sampling and analyzes of blister gases they concluded that the gases are the same as for normal air, and that gas-producing biological and chemical activity is small if present and unlikely as the main cause to blistering.

The importance of pavement permeability properties in relation to the blister formation was emphasized by Sasaki, Moriyoshi and Hachiya (2006). In surface courses of asphalt pavements where the coefficient of water permeability falls below a certain threshold (about 10^{-6} cm/s or less) liquid water cannot permeate and can block the pores as pore water. The sealing effect of the pore water can act as a barrier for vapor permeation and allow the blistering phenomenon to occur.

A preliminary study to this master's thesis found the most likely cause of the phenomenon to be trapped air and moisture within the pavement which expands and evaporates upon heating. This is also the most common perception of the problem among researchers. For this to occur, the asphalt concrete layer above and below the blister must have such a low permeability that pressure can build up at a faster rate than it can escape during heating of the asphalt pavement. Findings in this paper also indicate that for blisters to occur there must also be a significant volume of trapped air and moisture below the surface layer.

When the pavement overlay temperature subsides in the evening, the pressure inside the blister drops and the blister may contract. However, often the blisters do not contract completely and a small uplift in the overlay is still visible the next day. The reason for this can be attributed to the top down cooling, and the time- and temperature dependent viscoelastic properties of asphalt concrete that stiffens the overlay. This may also cause a negative pressure inside the blister, which allows it to inhale more air over subsequent days and thus explain observations of blisters growing over longer periods.

This study, being part of master's thesis at NTNU was initiated because of increasing occurrences of blisters in asphalt pavements at Norwegian airports and roads. It has focused on the thermodynamic and asphalt deformation mechanisms that occur during blister formation and has sought to gain a better understanding of these. Through theoretical review of the expansion of air and vapor gases, and the execution of a blister experiment using laboratory produced asphalt concrete slabs, these mechanisms were possible to investigate. In addition, it has considered the findings from this against preliminary investigations and observations of blisters on Norwegian roads and airports.

1.1 Discussion of experiences from blister cases at Norwegian airports and roads

In recent years blistering of asphalt concrete overlays on airports runways and roads seem to have become more apparent in Norway. Blisters with diameters typically about 20 – 100 cm have been observed forming on certain asphalt concrete overlays in warmer weather. There have mainly been reports about blister problems in structures with asphalt concrete overlays over asphalt concrete base courses, concrete pavements, or concrete bridge decks. They have been observed forming immediately after paving as well as after a while, and both new and old repaved pavements have experienced problems. **Figure 1** show a photo of a typical asphalt pavement blister.

Figure 1: Blister in a Norwegian asphalt pavement road (Hovin, 2018)

Few investigations of the phenomenon have been conducted in Norway and there is no thorough explanation for the problem. Only minor studies conducted by the NPRA (Norwegian public roads administration) have provided some information, and otherwise the available information is mainly through observations and documentation of cases. The preliminary findings from the NPRA investigations can be summarized as follows (Hovin, 2018):

- Analysis of core samples from national and county roads show that the layers above and below the blisters have a very low air-filled void percentage.
- High binder content in exposed areas.
- Some areas where examined for adhesive bond strength between new wearing course and levelling course. Results showed good bond strength.
- The blisters can come and go between seasons. Most prominent on hot summer days. Might be completely gone in wintertime, for then to return in the summer.

- PMB[†] both in the mixture and in the adhesive bonding is not a prerequisite for blistering.
- When the blisters are punctured, pressurized gas is released.
- Usually, the blister seems to occur between the wearing course and the binder course or leveling course and wearing course, but in some cases the blister pocket is observed forming in the layers themselves.
- The blisters have in some cases been observed to form immediately after, or during paving.

Site inspections of two airport runways with blister problems and discussion with airport pavement officials have led to the following manifestations.

- Same as for roads the blisters are usually gone in wintertime, for then to return in the summer.
- Blisters have been observed to form up to 2-3 months after resurfacing.
- The blisters have similar appearance to those appearing on roads, also with a release of pressurized gas when punctured.
- At one of the inspected airport runways, the loss of bond between aggregates and asphalt binder, and high porosity in the binder course were observed during resurfacing.
- The same runway was width extended with 3 m, and a large part of the blisters in the overlay have occurred over the joint between the old and new extended part.
- In the case for the other inspected airport a large part of the runway pavement is located on a rock-based embankment fill, whereas the other part is on a dense native material. Blisters have been observed to form only in the pavement over the dense native material subgrade.
- Both runways have had no blister problems in the past.
- Two methods are used to mitigate and prevent further damage to the pavement. One consists of drilling a hole in the blister to release the pressure, inject bitumen emulsion in the hole and pressing down the blister to adhere it to the subsurface. When this method is used, the blister does not appear in the same place again, but a new blister may appear elsewhere. The second method, usually done for the biggest blisters, consists of cutting and removing the blister and surrounding area. The removed area in the overlay is then repaved.

The above findings and manifestations indicate that gas expansion can be a driving mechanism in blister formation since the blisters occurs only in warmer weather. At the same time, it undermines the hypothesis that gas-producing chemical reactions are the main cause because then the blisters should have been observed to a greater extent during colder weather as well. However, the resistance to deformation in the asphalt overlay is higher at lower temperatures and this means that higher pressures is required to cause blisters. Therefore, gas-producing reactions cannot be completely ruled out as the cause of the gas overpressure. Observations of blisters occurring in overlays over underlying asphalt joints and porous binder courses may also indicate that where there are larger volumes of trapped air, the probability of blisters is greater. In addition, the absence of blisters on the rock-based embankment fill could indicate that any pressure

[†] Polymer modified bitumen is the modification of bitumen by the addition of rubber. Polybutadiene, polyisoprene, natural rubber, butyl rubber and chloroprene, among other rubbers, have all been used to modify bitumen. The effect is mainly to increase the viscosity of the bitumen (Hunter, Self and Read, 2015).

buildup is vented downward into the filling, while in the dense native subgrade the pressure cannot evacuate downwards and therefore cause blisters.

2 Thermodynamic blister analysis and properties of asphalt pavements

2.1 Blister mechanisms

The most common perception of how blisters arise is that a water and/or gas-filled pocket is created in between the different asphalt layers, and that temperature variations during day and night causes them to grow. This theory puts blistering in the category of moisture related damages, because there often is an intrusion of water or moist air in order for the blister to form (Kandhal, Lubold Jr and Roberts, 1989).

The blisters form as a result of a gas overpressure that uplift the asphalt overlay until equilibrium force is achieved between the force generated by pressure inside the blister, the weight of the asphalt layer, resistance to deformation in the layer and the adhesive bond resistance. The gas pressure is believed to occur because of air expansion and vapor pressure when the pavement is exposed to solar radiation. Asphalt concrete pavements usually have a low albedo‡ of about 0.05-0.25, depending on several factors such as age, aggregate material, color and more. This allow asphalt concrete overlays to achieve high surface temperatures even at relatively low air temperatures (Alleman and Heitzman, 2019). The absorbed thermal energy is then emitted to the surroundings and into the subsurface where it heats up trapped air and moisture. In Norway, surface temperatures in asphalt concrete overlays can reach over 50°C on the warmest days (Aurstad *et al.*, 2016). Under certain conditions the temperature may also drop rapidly, especially if there is rainfall. **Figure 2** illustrates the mechanisms believed to cause the blister phenomenon.

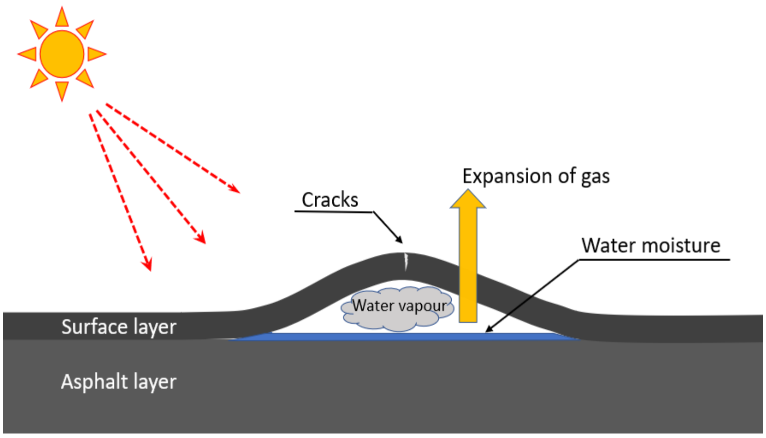

Figure 2 : Blister mechanisms (CERI, 2008)

‡ The albedo of a pavement surface describes its ability to reflect incoming sunlight and is quantified on a scale of 0 to 1. High-albedo pavements, including those constructed or coated with materials that are whiter or more reflective than ordinary pavements, will reflect more incoming solar radiation than darker pavements. Solar insolation energy that is not reflected, though, is absorbed, such that low-albedo pavements will then absorb more of the incoming solar energy than high-albedo pavement (Alleman and Heitzman, 2019, p.1).

2.1.1 Blister pressures

Using thermodynamic theory, we can estimate what pressures to expect during a blister formation. Under ordinary conditions air can be treated as an ideal gas and the combined gas law equation can be used to estimate the change in pressure and volume for a given change in temperature.

With the assumption that final volume V_2 of a blister is the same as initial volume V_1 ($V_1 = V_2$), we can calculate the maximum pressure occurring because of air expansion.

For a given pavement temperature change, the increase in gas pressure is given by:

$$P_{a2} = P_{a1}\left(\frac{T_2}{T_1}\right)\left(\frac{V_1}{V_2}\right) \tag{1}$$

Where:

T_1 = Initial absolute temperature

T_2 = Final absolute temperature

V_1 = Initial volume

V_2 = Final volume

P_{a1} = Initial pressure

P_{a2} = Final pressure

For constant volume ($V_1 = V_2$), maximum air pressure at a temperature increase from 10°C (283 K) to 50°C (323 K) is:

$$P_{a2} = P_{a1}\left(\frac{323}{283}\right) = 1.14\ P_{a1}$$

This shows that because of gas expansion the pressure inside a blister can increase by up to 14% for this change in temperature, provided the volume is constant. Or, if there is assumed no pressure change the volume can increase with the same 14%.

Beijers (1976) managed in a laboratory experiment to get a growing blister in the interface between a concrete slab and waterproof asphalt mastic without the presence of water. With the use of artificial solar radiation over the course of 2.5 hours per day the blisters grew 1-4 mm in height each day, and after 11 days a blister height of about 17 mm was achieved. Although this indicates that moisture inside the blisters may not be necessary for formation, is it generally believed that moisture usually is present in the blisters and that vapor pressure is a contributor to the total pressure.

Hironaka and Holland (1986) conducted a thermodynamic analysis of asphalt pavement blister gases. They showed that from 26.7 °C to 57.2 °C, a vapor pressure increase of 20.7 kPa to 27.6 kPa absolute pressure in a imagined blister volume of 1786 cm^3 only required 0.1 cm^3 of water. Such a small amount of water is reasonable to assume can be present in the subsurface layers and inside the blisters. As mentioned by Lai (1986), this also means that at the same temperature the addition of more water in the blister will not lead to increase in pressure because the air is already saturated, and further growth of the blister require the entry of more air.

Saturated vapor pressure of a liquid inside a closed container is the point where equilibrium between molecules moving between liquid phase and gaseous phase is reached (also called equilibrium vapor pressure). The pressure exerted from molecules in the gaseous phase is known as the vapor pressure, and when the liquid is exposed to higher temperatures the kinetic energy of the water molecules increases. This increases the number of molecules transitioning into vapor, which leads to a higher vapor pressure (Derry, Connor and Jordan, 2009).

By using the Antoine equation, the approximate saturated vapor pressure of water can be calculated:

$$log_{10} P = A - \frac{B}{C+T} \quad (2)$$

Where:

P = Pressure in kPa

T = Temperature in °C

A, B and C = Constants, for temperature range -5°C – 135 °C, A=7.16728, B=1716.984, C= 232.538 (Rodgers and Hill, 1978).

The saturated vapor pressure of water from 0 – 70 °C is shown in **Figure 3**.

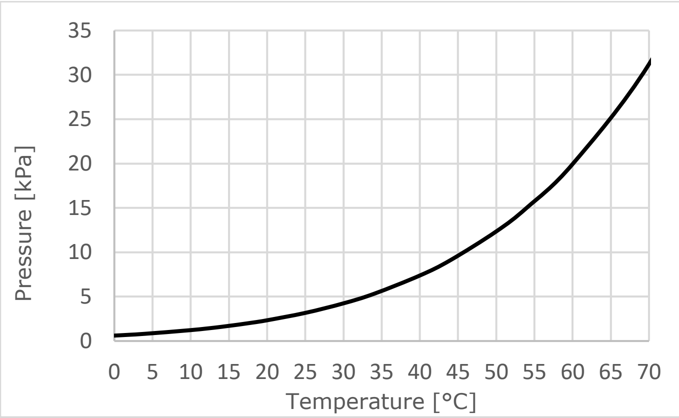

Figure 3: Saturated vapor pressure of water

The total pressure in a blister is calculated using Dalton's law of partial pressures. The total pressure by a mixture of gases is equal to the sum of the partial pressures of each of the constituent gases.

$$P_T = P_a + P_{sv} \quad (3)$$

When calculating the total of both saturated vapor pressure and air pressure, the initial temperature chosen affects the value of the final pressure. Lower initial temperature results in a higher final pressure at the same final temperature. Estimating a reasonable initial temperature for an analysis can be difficult since the temperature in the asphalt surface layers varies widely throughout the seasons, and the initial temperature at which the blisters are formed will likely vary.

Using the thermodynamic theory above, a calculation of blister pressures that may occur under Norwegian temperature conditions was made to determine if it could explain the blisters. In the calculations the initial temperature was set to 10°C. This is slightly higher than the annual average temperature at the inspected airports in this study, which is about 5-6°C (NPRA, 2018). To verify the equations and calculated values, the pressures was also measured using a test device. The test device consisted of a 308.5 cm^3 glass bottle containing 150 cm^3 of water and with a pressure sensor connected on top (photo of the test device is shown in appendix). **Table 1** shows the calculated and measured blister pressures up to a temperature of 55°C when relative humidity (RH) is at 100%, initial pressure P_1 at 101,3 kPa (1 atm) and initial temperature is 10°C. Volume is assumed constant in this analysis.

Table 1: Calculated and measured blister pressures

Temperature [°C]	Air pressure P_a (calculated) [kPa]	Saturated vapor pressure P_{sv} (calculated) [kPa]	$\Delta P = P_T - P_1$ [kPa]	Measured gauge pressure [kPa]
10	100.1	1.2	0.0	0.0
20	103.6	2.3	4.6	3.6
30	107.2	4.2	10.1	9.1
40	110.7	7.4	16.8	15.4
50	114.2	12.3	25.2	24.5
55	116.0	15.7	30.4	29.2

At all temperatures, the measured pressure showed slightly lower values than the calculated ones. A similar analysis was also performed by Wang et al. (2019) for a different temperature range. They also reported somewhat lower measured pressure values than calculated and attributed the reason for this to lie in the fact that air is not an ideal gas. This is also believed to be the cause in this case, in addition to that measurement inaccuracies may have occurred. The difference between the pressure values is shown in **figure 4**.

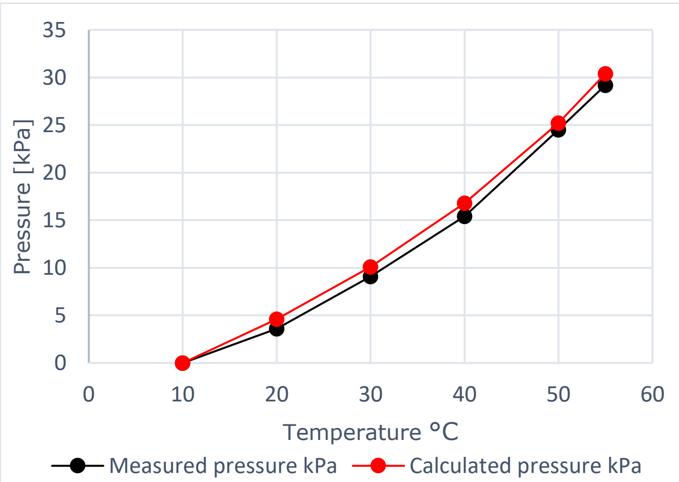

Figure 4: Calculated and measured pressure

2.1.2 Blister volumes

By using equation (1) and the calculated blister pressures, the maximum volume expansion in a blister can be calculated. If the pressure in the blister first is assumed to rise to P_2 = 131.7 kPa at 55°C with no volume increase, and then drop from 131.7 kPa to P_1 = 101.3 kPa at constant temperature 55°C, the increase in blister volume will be as follows:

$$V_2 = V_1\left(\frac{T_2}{T_1}\right)\left(\frac{P_2}{P_1}\right) = 1.3\ V_1$$

This means that the maximum theoretical volume a blister can increase by at the given temperature conditions, when no intrusion of outside air is occurring, is about 30 % of the initial volume. Therefore, the initial volume of the trapped air-filled voids under the surface layer may determine how large the blister can become, or how many blisters that will form. If the initial volume is very small, the blister growth will be less, and the blister will more likely contract to conform to the substrate when the temperature drops.

In some cases, the blisters have been observed to increase in size over subsequent days with warm weather. This indicates that over the course of 24 hours there could be an process which allows more air to enter the blister than what escapes. Lai (1986) suggested an explanation to this phenomenon which involves several mechanisms. At sunrise, the pavement starts to warm up from the top down, this reduces the stiffness (modulus) of asphalt. Softening of the binder and expansion of the pavement because of temperature increase also causes the pavement to seal some air voids and can reduce the permeability. Eventually, the temperature of the air and moisture inside the blister will start to rise and will try to expand thus increasing the pressure. Some of the air inside the blister may escape through interconnected air voids, but this does not happen rapidly enough to avoid pressure buildup. At the point where temperature inside the blister is at its highest, the asphalt pavement is at its softest stage. This puts more stress on the adhesive bond and could lead to bonding failure. Failure of the bond increases the diameter and volume of the blister and leads to reduction in the pressure which may temporarily halt the growth of the blister. When the sun goes down or it starts to rain the asphalt overlay cools down, again from the top down. Lower temperatures increase the modulus of the asphalt concrete, resisting the blister to fully contract to conform to the contraction in the air upon cooling. Because of this, a negative pressure can occur inside the blister. Shrinkage of asphalt overlays can also cause micro cracks and opening of pores which increases the permeability. Together these mechanisms allow the blister to inhale more air (Lai, 1986). An additional mechanism that also can facilitate both the inhalation of air in the blister and the prevention of pressure evacuation during heating, is that the viscosity of gas (air) is affected by the temperature and humidity of the air. When temperature decreases and humidity increases, the viscosity decreases, and vapor permeation becomes easier, and vice versa. Sasaki, Moriyoshi and Hachiya (2006) estimated that the change in gas permeability because of this phenomenon could be up to 30%.

2.2 Properties of asphalt pavements in relation to blistering

Aggregates, binder, and additives are the three main components in asphalt concrete. The complexity and composition of these materials together, makes asphalt concrete a very complex material. Even small adjustments in components and/or composition can significantly alter pavement performance and affect the formation of blisters. Important factors of asphalt concrete pavements in relation to blistering is thought to be the thickness of the layers, overlay albedo, water and gas permeability and rheological properties provided by the binder. In addition, the initial volume of trapped air below the surface layer and the adhesive bonding strength between the layers could affect the blister formation. As mentioned in Chapter 2.1, an asphalt overlay albedo will depend on several factors and is in itself a complex value to estimate. Therefore, this has not been studied in depth, but generally a lower albedo may result in higher surface temperatures and higher blister pressures.

2.2.1 Permeability

Sasaki, Moriyoshi and Hachiya (2006) examined the moisture transfer mechanisms in bituminous pavements with focus on measuring the coefficient of permeability of both water and humid air. At coefficients of water permeability 10^{-6} cm/s or lower, liquid water cannot permeate, and the water can block the pores as pore water. This makes the overlay vulnerable to blistering. However, it is possible that water vapor still can penetrate the overlay if the pores are not blocked by water. They also found a clear upper threshold for the gas permeability where blisters can occur at about 10^{-7} cm/s (i.e. all the core samples from blistering area that where examined in the study had a gas permeability at this order or lower).

Usually there is not set any requirements by the NPRA or Avinor[§] to the permeability coefficient during asphalt pavement construction, and it is not measured either. There is however a strong correlation between the air-filled voids and asphalt pavement permeability. A high percentage of total voids will generally correlate with a high percentage of interconnected voids. Higher levels of air voids result in a much greater likelihood of flow channels within the asphalt concrete (Vardanega, 2014). Requirements are therefore often set to the air-filled and binder-filled voids, usually with the goal of ensuring that the surface layers are impermeable to water. A normal AC 11 overlay has a permeability coefficient of 10^{-7} – 10^{-10} m/s and is assumed to be impermeable when the air-filled voids at all areas are less than 3.0% (Avinor, 2013).

The most desirable would be that the overlay is impermeable to water but still permeable to gas, allowing the overlay to breath. This can be difficult to achieve in most practical cases since the limit values for the permeability coefficient can become very narrow. However, development of new methods for easy measurement of the permeability during compaction may resolve this.

2.2.2 Rheological properties of asphalt concrete

The rheological properties of bitumen give asphalt concrete its flexibility. Bitumen is characterized as a thermoplastic, viscoelastic liquid, and it has a glass-like elastic behavior at low temperatures and/or during short loading times. At these conditions, the material responses can be described using Hooke's law. At high temperatures and/or during slow loading conditions it behaves as a viscous fluid. These properties make the stress response in bitumen highly dependent on temperature and loading time (Hunter, Self and Read, 2015).

While the bitumen is responsible for the viscoelastic properties in asphalts, the elastic and plastic properties are influenced by the mineral skeleton. The mechanical properties of viscoelastic materials differ from plasticity in that viscoelastic materials show a time-related recovery mechanism when a load is removed. This mechanism is referred to as delayed elastic response. During loading, asphalts can show a mixed viscoelastic and plastic response in which a proportion of deformation occurs. The proportion of each will generally depend on the loading time and on the temperature of the asphalt material (Hunter, Self and Read, 2015). During blister formation, the loading time can be long and the temperature high. Therefore, it is believed that the proportion of viscous response will dominate in the total deformation that occurs. **Figure 5** show the stress – strain

[§]Avinor is a wholly-owned state limited company responsible for planning, developing and operation of Norwegian state owned airports.

response in a creep and recovery test of bitumen and illustrates the discussed mechanisms.

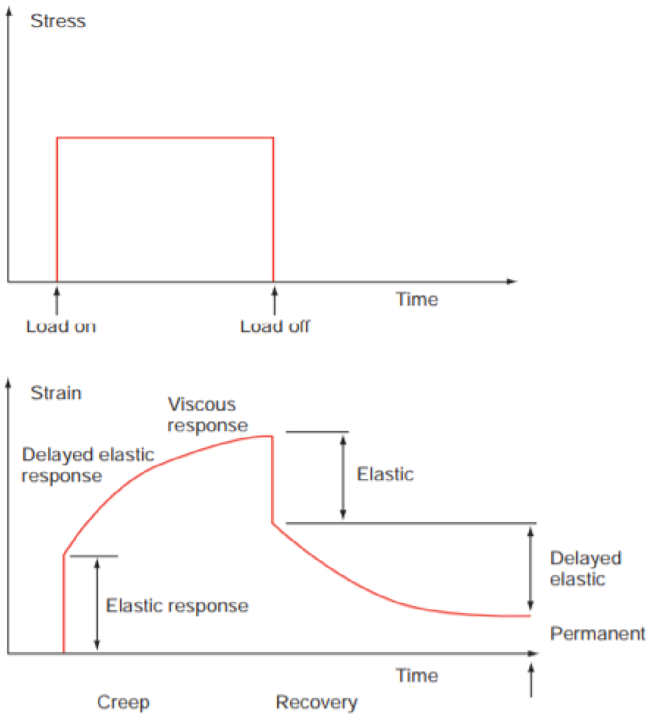

Figure 5: Stress–strain response during a creep and recovery test of bitumen (Hunter, Self and Read, 2015)

2.2.3 Volume of trapped air and moisture

As discussed in chapter 2.1.2 the initial volume of air and moisture that is trapped beneath a blister susceptible surface layer is an important factor. It is possible for quite large volumes of air and vapor to be trapped, especially in large paved areas such as airport runways. In narrower structures such as roads, it is reasonable to assume that any overpressure will be vented out to the sides of the structure more easily, and that the blisters that do occur will be more prevalent at some distance from the edge.

The amount of air-filled voids in asphalt concrete surface and base courses usually vary between 2-8 % (NPRA, 2018). Additionally, due to the rough surface properties of asphalt concrete mixtures, there will be some air-filled voids in the interface between the layers as well. In addition to the normally occurring volume of air-filled voids in asphalt pavements, there may be certain cases where this volume is considerably larger. This may be due to subgrade conditions, pavement damage or properties/structural design. Some examples of possible damages or pavement properties that may cause this are:

- Width extensions or poorly executed joints between paving lanes that cause sealed pockets of air and moisture under the overlay.
- Particularly porous binder courses due to for example, inadequate compaction or stripping damage.
- Open graded pavement with an impermeable overlay laid over a dense native subgrade such as clay.

Although not specified as the most important consequence in the literature, the presence of stripping damage could result in the asphalt layer being more porous. Stripping is when the adhesive bond between the aggregate surface and the asphalt binder is broken, leaving the mixture weakened. An asphalt mixture derives its strength from the cohesion resistance of the binder and aggregate interlock, and the frictional resistance of the aggregate. If the bonding between the binder and aggregate is reduced, the cohesion resistance will not be fully available. Several mechanisms can cause this damage, however the presence of moisture is a common factor to all stripping (Taylor and Khosla, 1983). Increased pore volume because of this process will allow a larger accumulated volume of air and moisture beneath the overlay. Since moisture is already present during the stripping process, the trapped air will easily become saturated and the addition of vapor pressure will be achieved under blister formation. Lai (1986) also reported varying degrees of stripping in several core samples taken from asphalt overlays and subsurface in blistering areas. He pointed out that stripping will, in addition to weakening the overlay, also cause the bonding strength between the tack coat and the overlay and/or subsurface to be weakened.

Usually, an assumption is made that the pressure buildup within each blister is one contained/sealed environment. This may not always be the case, as it is physically possible that one sealed environment may contain several blisters. There is also no reason to assume that the sealed environment for each blister cannot extend far from the blister itself. The sizes of the observed blisters and the expansion potential calculated in chapter 2.1.2 indicate that it will be virtually impossible that the sealed environment of a blister is bounded only by the area of the blister since the volume of trapped gas will not be sufficient. With this in mind a simple calculation was made to determine if the volume of air-filled voids required to create blisters in a runway/road structure is reasonable.

An area of 3x3 m in a typical runway/road pavement structure has an impermeable asphalt concrete overlay, and a 5 cm thick asphalt concrete binder course beneath. The binder course has a total of 8 % interconnected air-filled voids including the voids in the interface between the layers. The deeper layer is assumed to be impermeable to gases.

Total volume of air and vapor within the voids in the binder course will be:

$$V = 3m \cdot 3m \cdot 0.05m \cdot 8\% = 36\ dm^3$$

Assuming there is enough moisture to completely saturate the air within the layer, and by using the maximum volume expansion of 30 % found in chapter 2.1.2, the volume expansion potential will be:

$$V = 36\ dm^3 \cdot 30\% = 10.8\ dm^3$$

It is reasonable to assume that this volume expansion potential is sufficient for one or more blisters to occur in the given area. However, the binder course in this example can be characterized as porous. If the interconnected air-filled voids had been only 2%, the volume expansion would have been only 2.7 dm^3. Therefore, this may be a decisive factor as to whether blisters will occur or not.

3 Materials & Methods

3.1 Methods

Solving the problem of blisters in asphalt concrete overlays require identifying factors and mechanisms that are involved in the blister formation. Steps to reduce or eliminate the blistering problem can only be taken when there exists a good understanding of these. The complexity of the problem, and the many factors that may play a role in it means that the problem must be solved by thoroughly evaluating possible factors and causes step by step. This study has aimed to identify and discuss some of these factors and mechanisms.

3.2 Materials tested

3.2.1 Laboratory produced asphalt concrete slabs

The blister experiment in this study has been performed using laboratory produced 30x30x4 cm and 30x30x3 cm asphalt concrete slabs (AC11). These slabs were initially produced to define asphalt mixture rutting performance in a wheel track test but were considered useable for this experiment as well. Preferably, the slabs should have been somewhat larger, but this would have required other production equipment that was not available at the time. Two 4 cm thick slabs and one 3 cm slab where tested. The 3 cm thick slab where initially produced as a 4 cm thick slab, but where cut down to 3 cm. Outline of this asphalt mixture is shown in **table 2**.

This asphalt concrete mixture is widely used on airports and roads in Norway, but with varying binder specifications and often with use of PMB (polymer modified bitumen).

Table 2: Outline asphalt mixture (AC11)

Asphalt concrete 11	
Type of mixture	Dense
Max aggregate size [mm]	11
Air voids [%]	2-5
Asphalt content [%]	5,5
Asphalt binder	70/100

3.3 Test methods

3.3.1 Blister experiment

The main objective of this experiment was to find out if temperatures achievable in an asphalt concrete pavement could create a pressure due to air expansion and vapor pressure high enough to cause a blister. It was also investigated how temperature variations affect blister growth and shrinkage. By monitoring the pressure and temperature inside a blister during cooling and contraction, the results could possibly give a more thorough understanding of the blister mechanisms. There is no procedures or standardized methods that exists for this type of analysis. Therefore, the experiment methods were mainly based on ideas and trial and error.

3.3.2 Test model

A laboratory asphalt concrete slab with mixture requirements as presented in chapter 3.2.1 was placed on a 12 mm thick aluminum plate with several 10 mm drilled holes. A 1 mm thin rubber membrane was also bonded to the underside of the asphalt concrete plate to ensure that the blister void was completely sealed around the edges and to avoid pressure leakage. Then a steel box with dimensions 24x24x10 cm and a total volume of 5760 cm^3 was bolted to the underside of the aluminum plate to create a large enough initial volume. Finally, a steel frame surrounding and on top of the slab were used to prevent the of possibility for the slab to freely expand and to lock it in place. This gave a unbonded area of 26x26 cm for the blister to occur on.

The asphalt slab temperature was measured with an infrared thermometer, while the gas temperature was measured with a K-type thermocouple connected to a multimeter. Gauge pressure inside the model was measured using a SUNX DP2 digital pressure sensor. Accuracy of the measured temperatures was +/- 2% for the infrared thermometer and +/-3% for the K-type thermocouple. For the digital pressure sensor, the repeatability was +/- 0.2%. All values were logged manually.

Before the experiment was started, the test model was filled with 20 ml of water and stored at an outside ambient temperature of about 4°C. This amount of water is sufficient for the air in the model to become fully saturated. Then it was brought inside to a room temperature of about 24°C where it slowly could warm up to where the asphalt slab surface temperature reached a temperature of about 10°C. At this point, the model was sealed and immediately placed in an oven at a temperature of 50-60°C. **Figure 6** shows a sketch of the test model.

It is important to note that the conditions under which this experiment was prepared and performed were not ideal controlled laboratory environments. This means that the precision of the measurements was not optimal, and it may have led to unknown sources of error. When using the results, this must be considered. The reason for the lack of controlled environment is described in the appendix.

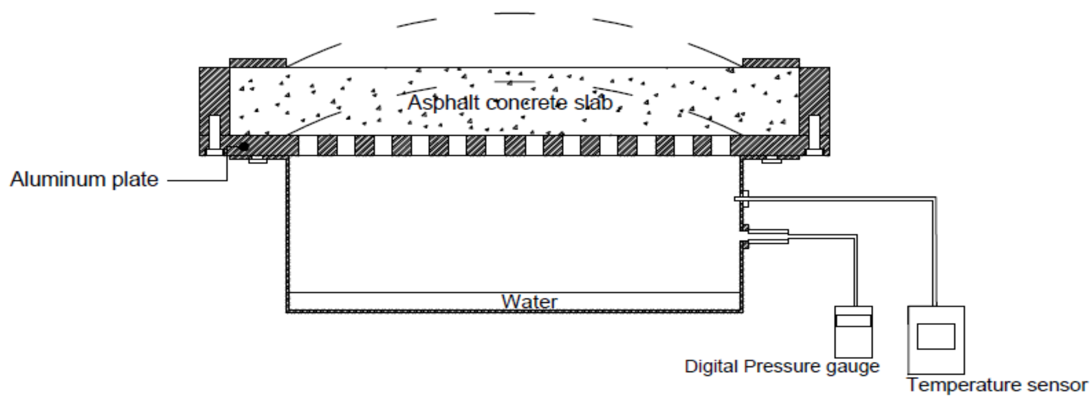

Figure 6: Test model for blister experiment

4 Results & discussion

4.1 Results blister experiment

The results from the blister experiment showed that vapor pressure and expansion of air can produce sufficient pressure to form a blister in a 3 cm and 4 cm thick asphalt overlay. After 30-50 minutes of heating with a starting temperature of 5-8 °C the gas temperature had reached 25- 32 °C and a measurable blister height of 1-3 mm had occurred in all the tested asphalt concrete slabs. The three slabs were tested at slightly different maximum temperatures, and only test 2 and 3 included the cooling phase. This was because in test 1, large cracks occurred at the top of the blister towards the end of the test and the blister was considered to be broken.

The results are illustrated by plotting the parameters blister height versus gas and slab temperature, and blister height versus gauge pressure. The complete datasets from all tests are included in the appendix.

In Figure 7, results from blister test 1 are presented. Within 30 minutes the pressure and temperature inside the model had risen to 9 kPa and 26°C, and a measurable blister had occurred. After 110 minutes of heating, the pressure and gas temperature had increased to 22 kPa and 53°C, and the measured blister height was 17.5 mm. At this point large cracks occurred, and the blister growth rate accelerated because of the reduced resistance to deformation. The blister was therefore considered to be broken, and the test was stopped because any registration of the cooling phase could possibly provide invalid data.

Figure 8 shows the test results from the 3 cm thick slab. As expected, the 3 cm slab showed earlier and faster growth in blister height. At a pressure of 7.8 kPa and temperature of 25°C, a blister height of 0.5 mm had occurred. During the test, the slab showed an exponential like growth up to a maximum height of 27 mm. After 100 minutes, the test rig was set to cool, while pressure and temperature were still monitored. The blister continued to grow after the cooling phase was started, and the blister height was maintained even though the pressure eventually dropped to 3 kPa.

Results from test 3, shown in **figure 9**, where performed in the second 4 cm slab and was run over 335 minutes. The last 120 minutes were in the cooling phase. The test was run at a lower maximum temperature than test 1 and consequently the maximum blister height was somewhat lower. As in Test 2, the height was maintained even after the cooling phase was initiated, and not until the pressure had dropped to about zero, began the blister height to decline significantly. However, the blister did not contract completely and towards the end there was recorded a negative pressure of 3.1 kPa inside the blister model.

In **Figure 10** a photograph of the blister occurred in test 1 is shown.

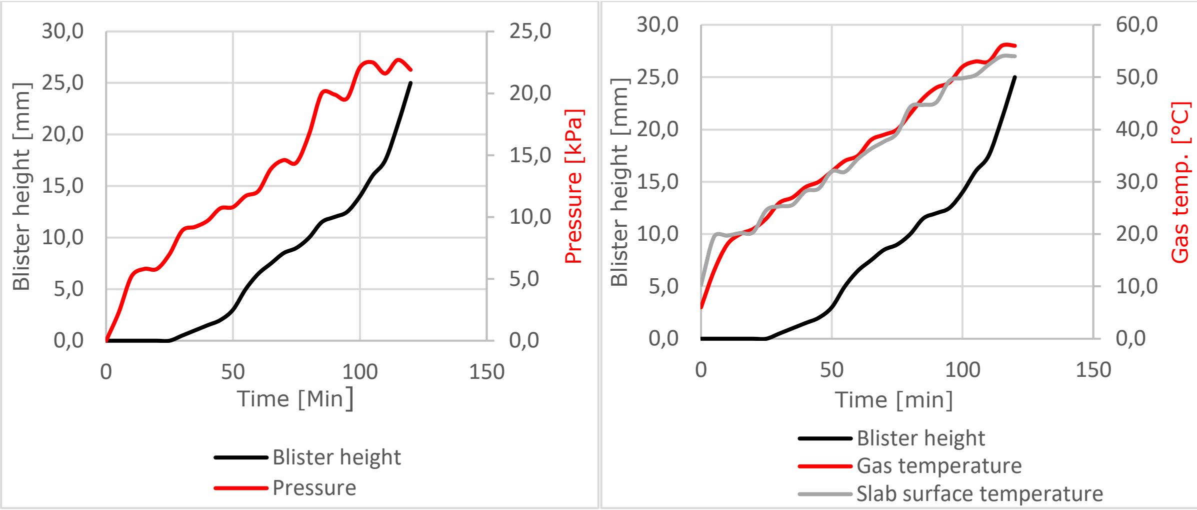

Figure 7: Blister test 1 (4 cm slab)

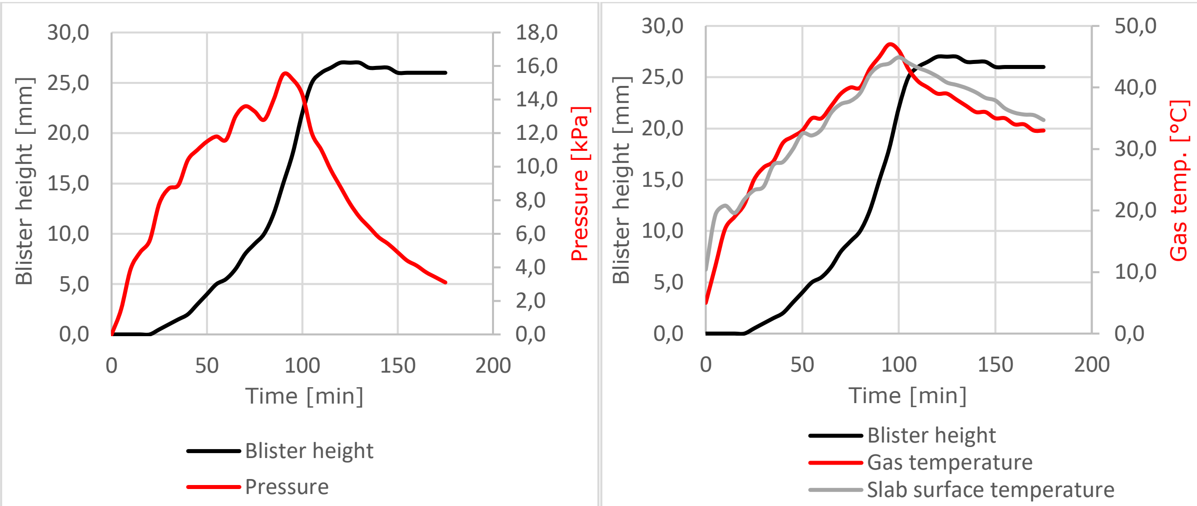

Figure 8: Blister test 2 results (3 cm slab)

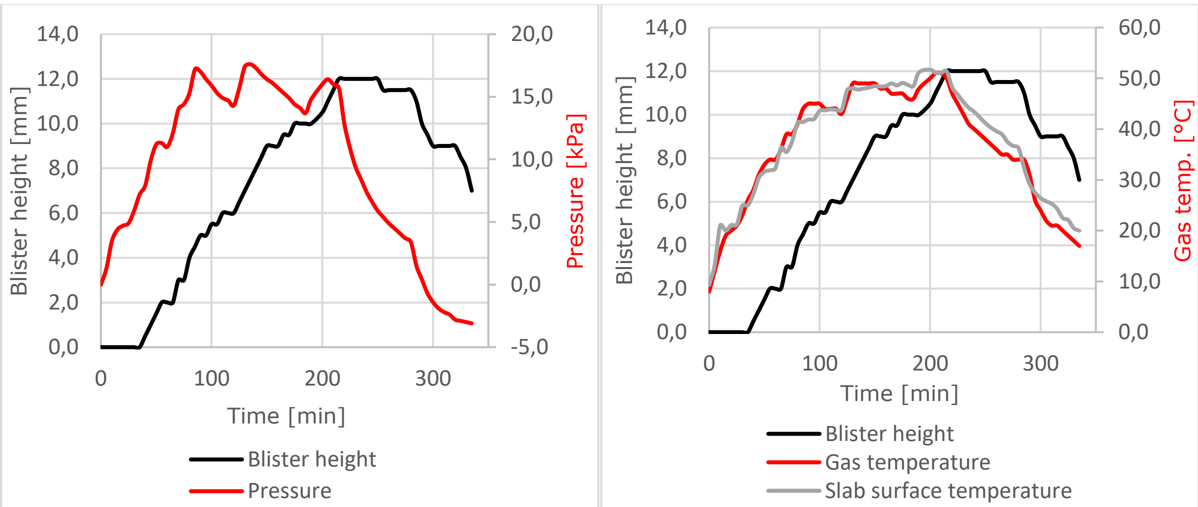

Figure 9: Blister test 3 results (4 cm slab)

Figure 10: Blister after test 1

The results show that even relatively low pressures and temperatures can cause blisters in an AC 11 overlay. In addition, this experiment was conducted over a shorter time perspective compared to a blister formation that could occur in a real life. Given enough time, it is likely that even lower pressures than those recorded in this experiment maintained over an extended period could be able to create as much blister height. On the other hand, the slabs in the test where not bonded to the substrate as would be the case in an asphalt pavement structure. Therefore, the initiation of a blister may require a higher pressure since some force will be required to break the adhesive bond between the layers. The results also correlate well with the reviewed theory and clearly shows that air expansion and vapor pressure in many cases could be a plausible cause of the blisters. However, in further investigations, the constituents of the gas contained in the blisters should be considered and examined. If no gas-producing chemical reactions can be detected, there are few other explanations for the blister formation.

Although this test model is not directly comparable to real conditions, it is believed to simulate the blister mechanisms that occur to a certain extent. Due to limited access to asphalt materials and laboratory equipment the test model was not possible develop further with features that would make it more comparable to a real asphalt pavement structure. The limitations of this experiment are mainly that the asphalt slabs were completely unbonded to the aluminum plate and that the area for the blister to occur was fixed. The observed blisters also often have a larger area than in this experiment and therefore the blister height can be higher as well. They will also have the possibility to grow in size as the adhesive bond breaks. Furthermore, it is important to point out that this experiment will not be comparable to a blister formation that occurs immediately after paving. During paving, the asphalt mixture temperature can be up to 140°C and the modulus of the asphalt concrete will be very low. In addition, the built-up gas pressure below the surface layer could be substantially higher.

5 Conclusions

Based on the thermodynamic analysis, on-site observations, and results from the blister experiment the following conclusions are drawn:

(1) For blistering to occur, the asphalt concrete overlay must have such a low permeability coefficient that a gas overpressure cannot escape.

(2) Air and moisture trapped in voids under an asphalt concrete overlay exposed to solar radiation can create pressures up to about 30 kPa under certain climatic conditions. The maximum pressure depends not only on the maximum temperature but also on the initial temperature at which the blisters are formed.

(3) Results from the blister experiment indicate that for a 3 cm and 4 cm thick AC11 overlay blisters can be initiated at relatively low gas pressures and surface temperatures. Gas pressures of 7-10 kPa and asphalt surface temperatures of 25-30°C were sufficient to initiate blisters in the unbonded AC11 slabs. This suggests that blisters can form also under normal summer conditions, and not only during so-called blistering heat.

(4) The experiment and thermodynamic theory have shown that for blisters to occur because of air expansion and vapor pressure caused by solar radiation energy, the initial volume of trapped air and moisture must be sufficient. Only a small amount of water intrusion is enough to saturate the air and thus get the full addition of vapor pressure. The amount of air and moisture that is trapped under an overlay may under normal conditions be sufficient for blisters to appear. Other properties and/or damages in the structural design may also cause even larger volumes of air than normal to be trapped, and this can make the overlay more prone to blistering. Some examples of this can be: Porous binder and/or base courses laid over impermeable subbase and subgrades such as clay or concrete, inhomogeneities in layers beneath the surface layer such as joints because of widening work and uneven resurfacing work, and stripping and cracks in the binder course.

(5) Summarized, the most important factors for avoiding blisters are thought to be:
    a. The asphalt concrete overlay must be ensured to be permeable to vapor gas.
    b. Very thin overlays should be avoided.
    c. Large voids of trapped air below the surface layer should be avoided, especially if the deeper layers in the pavement or the subgrade material are known to have low permeability.

(6) Suggestions for further work on the solving the blister problem should be to completely exclude that there are no gas-producing chemical reactions that could cause the gas overpressures. This can probably be done without the need for extensive and expensive research. Other investigations may include examining the condition of subsurface layers in blistering areas for possible factors that can lead to large volumes of air and moisture being trapped.

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Appendix

Appendix 1 – The coronavirus's impact on the work with the master's thesis

While working on this master's thesis, the sars-Cov-2 virus that originated in Wuhan, China was spread to large parts of the world with the consequence that drastic measures to limit the infectious disease of Covid-19 were initiated in the community in Norway. These measures included, among other things, the closure of educational institutions over a longer period. This affected this master’s thesis in a way that limited the scope of laboratory and field work in the project to what was originally planned, and it also affected the availability of special laboratory equipment. In addition to the experimental laboratory tests, the plan was to collect and analyze core samples from an airport exposed to problems with blisters in the asphalt concrete runway. The described situation meant that the project theme had to be investigated using other methods, and to a greater extent based on theory and work done by others. However, it still succeeded to prepare and perform the blister experiment without access to a professional laboratory using only simple mechanical equipment and ingenuity. Because of the circumstances the process of developing, as well as making the blister model work as desired, also became a rather large and time-consuming part of the master's thesis. The process of writing this paper, as well as development and preparation of the experiment can therefore be said to have taken place under non- ideal conditions.

Date
3 June 2020

Our reference

Faculty of Engineering
Department of Civil and Environmental Engineering

Your date

Your ref

To Whom it Might Concern

Master thesis spring 2020 - consequences of the Covid 19 pandemic

The pandemic situation in spring 2020 made it necessary to change or adjust the topic for master theses at NTNU. The university closed including laboratories and did not allow any type of field work, thus made it impossible to continue planned work for many students.

Sincerely yours

Inge Hoff

Inge Hoff
Professor

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This letter was sent to all students with specialisation in Transport, Road or Railways in the Civil and Environmental study program to be included as an attachment in their thesis.

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Appendix 2 – Blister experiment test results

Test nr. 1		
Oven temp. =	**60**	**°C**
Amount of water =	**20**	**ml**
Unbonded area =	**26*26**	**cm**
Thickness of slab =	**40**	**mm**

Time [min]	**Slab surface Temp. [°C]**	**Gas temp [°C]**	**Pressure [kPa]**	**Blister height [mm]**
0	10,3	6,0	0,0	0,0
5	19,5	13,0	2,3	0,0
10	19,7	18,0	5,2	0,0
15	20,2	20,0	5,8	0,0
20	20,4	21,0	5,8	0,0
25	24,6	23,0	7,0	0,0
30	25,3	26,0	8,9	0,5
35	25,6	27,0	9,2	1,0
40	28,2	29,0	9,7	1,5
45	28,7	30,0	10,7	2,0
50	32,0	32,0	10,8	3,0
55	31,9	34,0	11,7	5,0
60	34,4	35,0	12,1	6,5
65	36,3	38,0	13,9	7,5
70	37,7	39,0	14,6	8,5
75	39,3	40,0	14,4	9,0
80	44,3	43,0	16,7	10,0
85	44,7	46,0	20,0	11,5
90	45,2	48,0	19,9	12,0
95	49,3	49,0	19,6	12,5
100	49,8	52,0	22,1	14,0
105	50,4	53,0	22,5	16,0
110	52,4	53,0	21,6	17,5
115	54,0	56,0	22,7	21,0
120	54,0	56,0	21,9	25,0

Test nr.2

Oven temp. =	**55**	**°C**
Amount of water =	**20**	**ml**
Unbonded area =	**26*26**	**cm**
Thickness of slab =	**30**	**mm**
Cooling temp	**24**	**°C**

Time [min]	**Slab surface Temp. [°C]**	**Gas temp [°C]**	**Pressure [kPa]**	**Blister height [mm]**
0	10,4	5,0	0,0	0,0
5	19,3	11,0	1,5	0,0
10	20,8	17,0	3,9	0,0
15	19,6	19,0	4,9	0,0
20	21,8	21,0	5,6	0,0
25	23,3	25,0	7,8	0,5
30	23,9	27,0	8,7	1,0
35	27,4	28,0	8,9	1,5
40	27,9	31,0	10,4	2,0
45	29,9	32,0	11,0	3,0
50	32,5	33,0	11,5	4,0
55	32,2	35,0	11,8	5,0
60	33,2	35,0	11,6	5,5
65	35,9	37,0	13,0	6,5
70	37,3	39,0	13,6	8,0
75	37,8	40,0	13,3	9,0
80	39,1	40,0	12,8	10,0
85	42,1	43,0	14,0	12,0
90	43,5	45,0	15,5	15,0
95	43,9	47,0	15,2	18,0
100	44,9	46,0	14,3	22,0
105	44,0	43,0	12,0	25,0
110	43,2	41,0	11,0	26,0
115	42,6	40,0	9,8	26,5
120	41,8	39,0	8,8	27,0
125	40,8	39,0	7,8	27,0
130	40,4	38,0	7,0	27,0
135	39,9	37,0	6,4	26,5
140	39,2	36,0	5,8	26,5
145	38,3	36,0	5,4	26,5
150	37,9	35,0	4,9	26,0
155	36,6	35,0	4,4	26,0
160	35,9	34,0	4,1	26,0
165	35,6	34,0	3,7	26,0
170	35,5	33,0	3,4	26,0
175	34,7	33,0	3,1	26,0

Test nr.3

Oven temp. =	**55**	**°C**
Amount of water =	**20**	**ml**
Unbonded area =	**26*26**	**cm**
Thickness of slab =	**40**	**mm**
Cooling temp	**10**	**°C**

Time [min]	Slab surface Temp. [°C]	Gas temp [°C]	Pressure [kPa]	Blister height [mm]
0	9,3	8,0	0,0	0,0
5	13,2	12,0	1,3	0,0
10	21,0	16,0	3,5	0,0
15	20,0	19,0	4,4	0,0
20	21,1	20,0	4,7	0,0
25	21,2	21,0	4,9	0,0
30	24,9	23,0	5,9	0,0
35	25,0	26,0	7,2	0,0
40	27,2	28,0	7,9	0,5
45	30,4	31,0	9,9	1,0
50	31,6	33,0	11,2	1,5
55	31,9	34,0	11,3	2,0
60	32,3	34,0	11,0	2,0
65	36,3	36,0	12,1	2,0
70	35,5	39,0	14,0	3,0
75	37,5	39,0	14,4	3,0
80	41,2	41,0	15,3	4,0
85	41,4	44,0	17,2	4,5
90	41,9	45,0	17,0	5,0
95	42,0	45,0	16,4	5,0
100	43,6	45,0	15,9	5,5
105	43,7	44,0	15,3	5,5
110	43,9	44,0	14,9	6,0
115	43,8	44,0	14,7	6,0
120	43,8	43,0	14,3	6,0
125	47,7	46,0	15,7	6,5
130	48,0	49,0	17,4	7,0
135	47,8	49,0	17,6	7,5
140	48,0	49,0	17,3	8,0
145	48,2	49,0	16,8	8,5
150	48,5	49,0	16,4	9,0
155	48,4	48,0	16,1	9,0
160	48,5	48,0	15,7	9,0
165	49,0	47,0	15,3	9,5
170	48,6	47,0	14,9	9,5
175	49,1	47,0	14,4	10,0
180	48,7	46,0	14,1	10,0
185	48,5	46,0	13,7	10,0
190	51,2	48,0	14,8	10,0

200	51,7	50,0	16,0	10,5
205	51,1	51,0	16,4	11,0
210	51,1	51,0	16,0	11,5
215	51,4	50,0	15,7	12,0
220	48,2	47,0	12,8	12,0
225	46,8	45,0	10,9	12,0
230	45,4	43,0	9,4	12,0
235	44,2	41,0	8,4	12,0
240	43,4	40,0	7,4	12,0
245	42,3	39,0	6,6	12,0
250	41,2	38,0	5,9	12,0
255	40,3	37,0	5,4	11,5
260	39,6	36,0	4,9	11,5
265	39,0	35,0	4,5	11,5
270	37,5	35,0	4,1	11,5
275	36,7	34,0	3,7	11,5
280	36,3	34,0	3,4	11,5
285	32,4	34,0	1,5	11,0
290	29,2	31,0	0,4	10,0
295	27,5	26,0	-0,7	9,5
300	26,4	24,0	-1,4	9,0
305	25,8	22,0	-1,9	9,0
310	25,3	21,0	-2,2	9,0
315	24,3	21,0	-2,4	9,0
320	22,5	20,0	-2,8	9,0
325	22,1	19,0	-2,9	8,5
330	20,5	18,0	-3,0	8,0
335	20,0	17,0	-3,1	7,0

Appendix 3 – Calculated and measured blister pressures

Heating oven temp. =	**55**	**°C**
Amount of water =	**150**	**ml**
Volume of bottle =	**308,5**	**ml**

Water Temp.[°C]	Measured Pressure [kPa]	Calculated pressure [kPa]
10	0	0
20	3,6	4,6
30	9,1	10,1
40	15,4	16,8
50	24,5	25,2
55	29,2	30,4

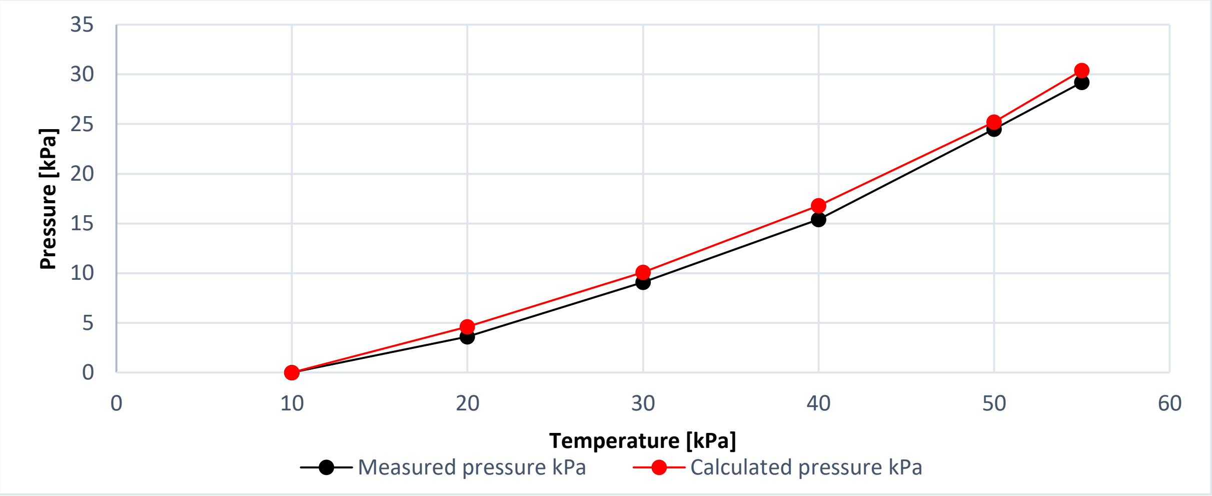

Figure 1: Calculated and measured pressure

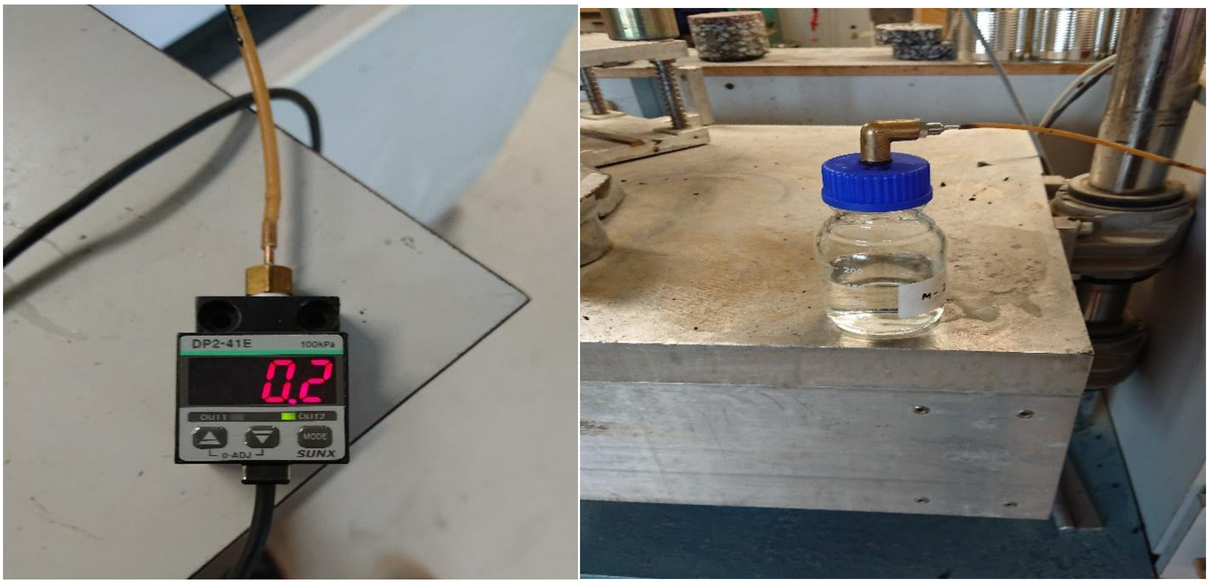

Figure 2: SUNX DP2-41E pressure sensor and bottle for measuring air and vapor pressure.

Appendix 4 – Calculation-Saturated vapor pressure of water

Temperature	Saturated water vapour pressure		
[°C]	[kPa], [100*bar]	[atm]	[psi]
0,01	0,61	0,01	0,09
2,00	0,71	0,01	0,10
4,00	0,81	0,01	0,12
10,00	1,23	0,01	0,18
14,00	1,60	0,02	0,23
18,00	2,06	0,02	0,30
20,00	2,34	0,02	0,34
25,00	3,17	0,03	0,46
30,00	4,25	0,04	0,62
34,00	5,33	0,05	0,77
40,00	7,38	0,07	1,07
44,00	9,11	0,09	1,32
50,00	12,35	0,12	1,79
54,00	15,02	0,15	2,18
60,00	19,95	0,20	2,89
70,00	31,20	0,31	4,53
80,00	47,41	0,47	6,88
90,00	70,18	0,69	10,18
96,00	87,77	0,87	12,73
100,00	101,42	1,00	14,71
110,00	143,38	1,42	20,80
120,00	198,67	1,96	28,82

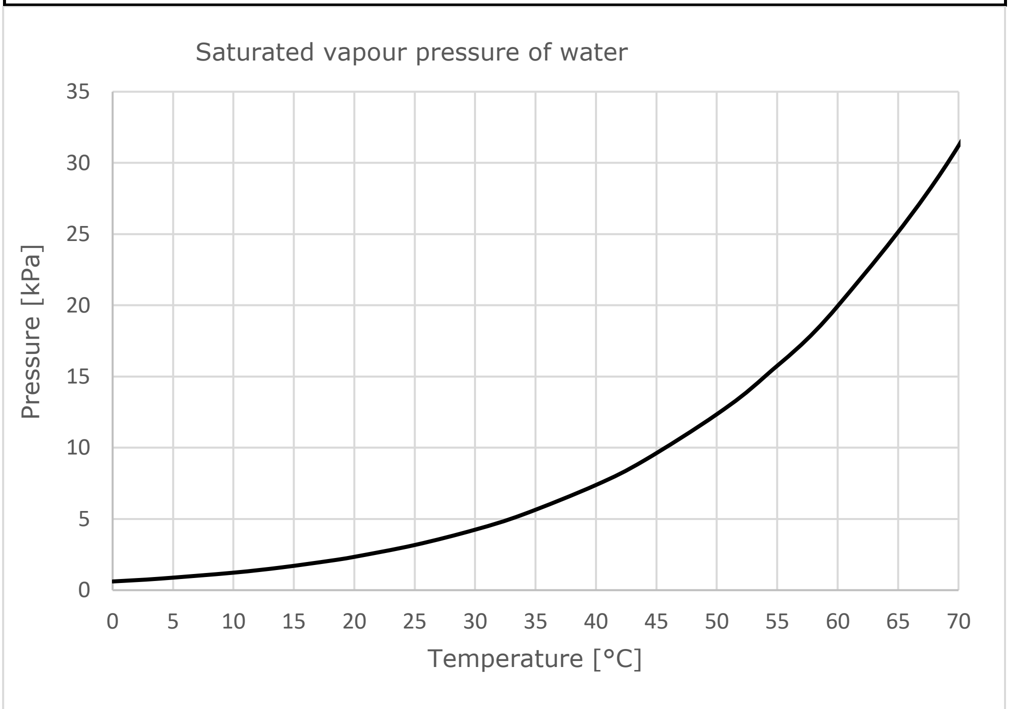

Figure 3: Saturated vapor pressure of water

Appendix 5 – Blister test model

Figure 4: Complete blister test model with measuring equipment.

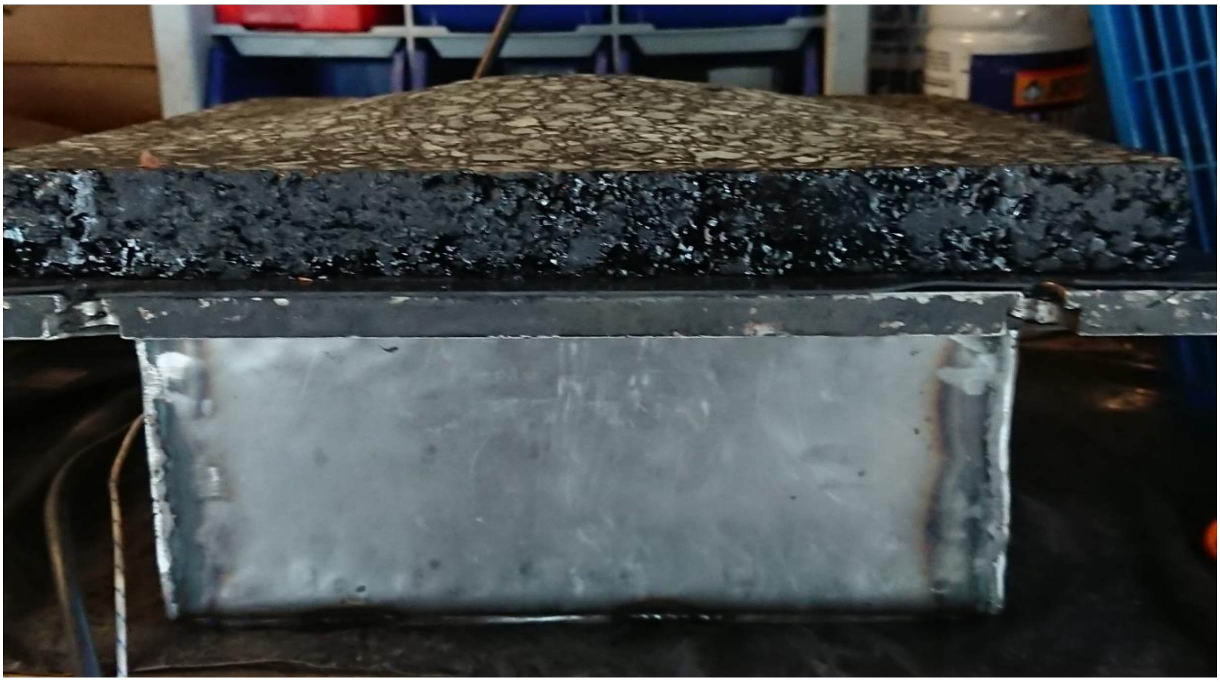

Figure 5: Remaining blister after cooling in test 2, with locking frame removed (3cm slab)

Figure 6: Steel box to be mounted underneath the aluminum plate.

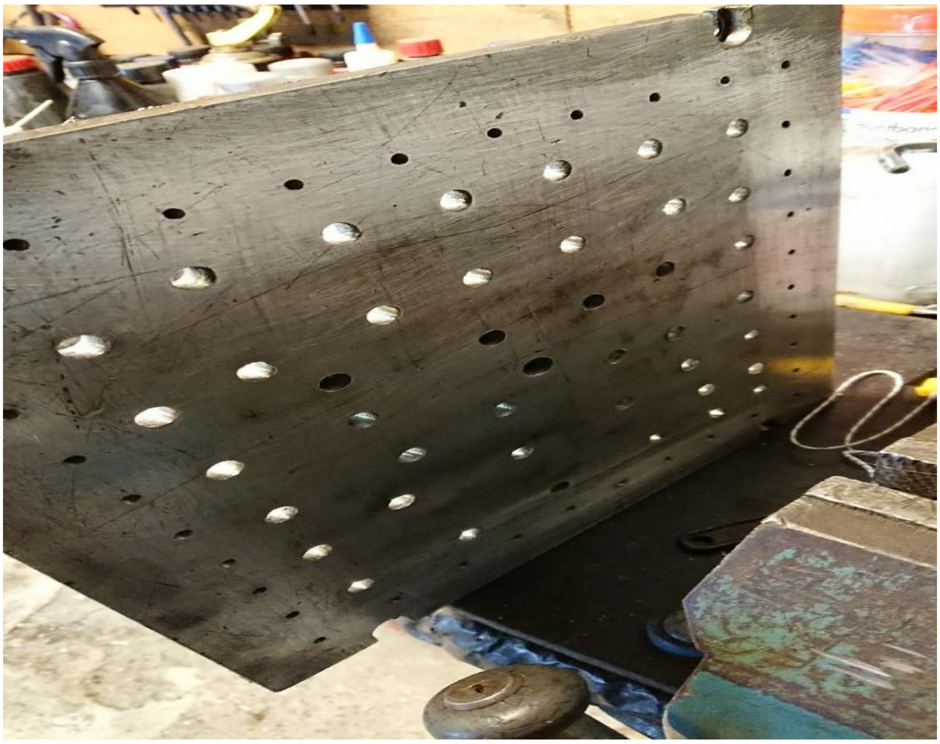

Figure 7: Aluminum plate for test model.

Figure 8: Blister from test 1 (4cm slab) with visible cracks on the top.

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