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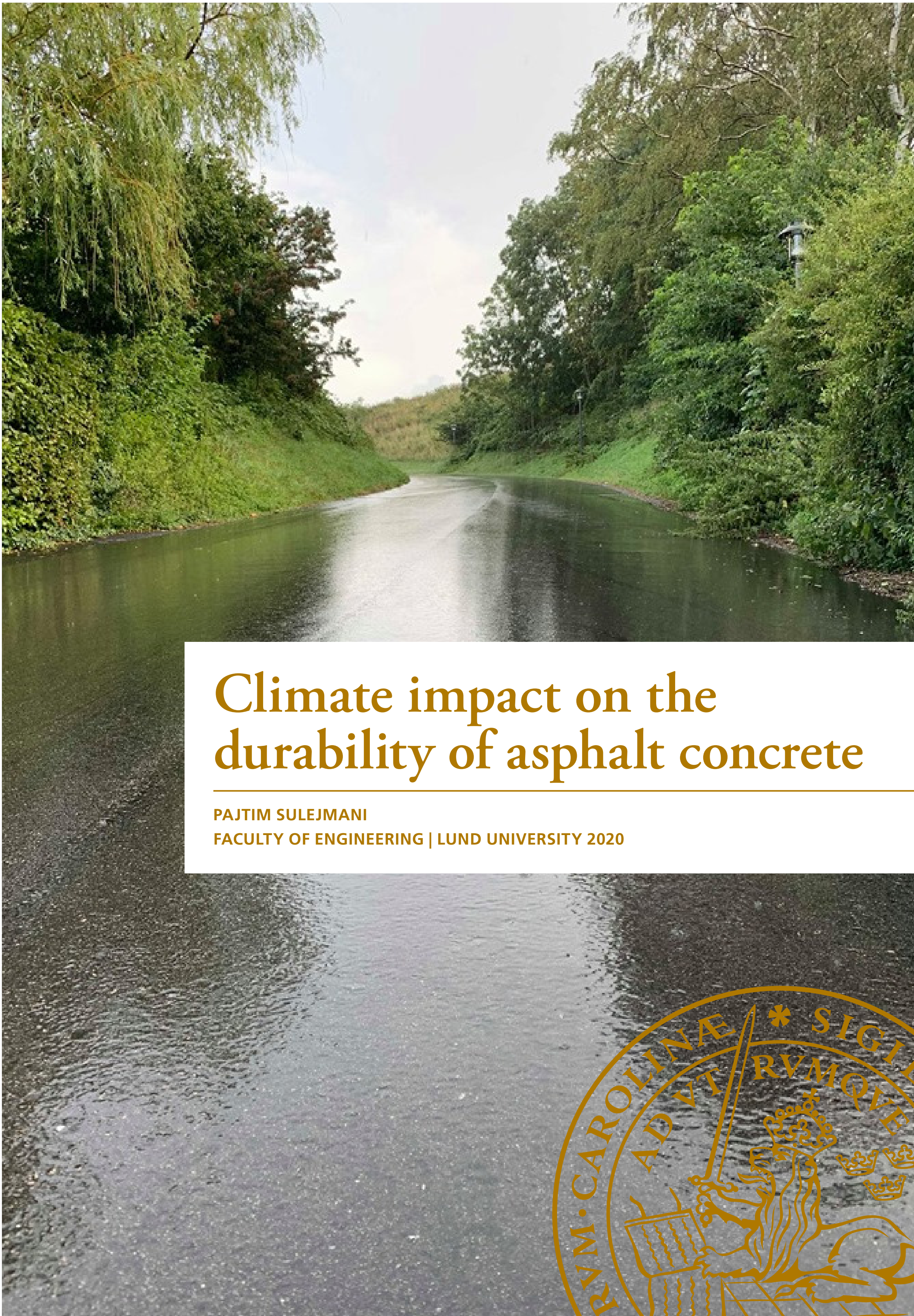

Climate impact on the durability of asphalt concrete

PAJTIM SULEJMANI
FACULTY OF ENGINEERING | LUND UNIVERSITY 2020

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Gratefully yours,

Pajtim Sulejmani

January 2020, Lund, Sweden

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Abstract

Roads are subjected to traffic loads and varying climate conditions that eventually lead to different types of damage. Moisture in asphalt is one of the major causes of premature failure in asphalt pavements. In addition, moisture in the unbound layers and temperature in the asphalt concrete (AC) layers affect the structural response of pavements under loading, such as the tensile strain at the bottom of AC layers. This thesis focused on identifying the influence of climate on the deterioration of flexible pavement and on the assessment of pavement performance with regard to variations of temperature and moisture content. Laboratory testing of AC with various mix compositions under repeated pore pressure loadings to quantify the influence of mix composition against moisture sensitivity was performed. The influence of climate parameters, i.e. moisture content and temperature on the tensile strain at the bottom of the AC layer, was also studied by means of a falling weight deflectometer and response measurements at full-scale pavement test sections. The results showed that binder content, air void content and pore pressure conditioning have a significant influence on the stiffness reduction of AC. In addition, the temperature and moisture content have yielded significant contributions towards explaining the strain at the bottom of AC layers. Relationships between climate impact and asphalt pavement properties have been proposed which may be useful in the evaluation and design of flexible pavement with respect to climate conditions.

Summary

A considerable portion of the road network in Nordic countries reaches premature failure within just five years. This has a significant economic and environmental impact due to the need for repeated maintenance. Roads are subjected to stresses from traffic loading and climate impact. The influence of non-traffic related parameters, such as temperature and moisture, must be understood for long-term pavement performance in light of the main sources of deterioration, e.g. cracking, rutting, stripping and degradation of asphalt mixture properties, and reduction of the stiffness modulus. The causes of such damage are difficult to characterise or predict, partly due to the complexity of the asphalt material and partly since they cannot be linked to one single phenomenon but rather several, such as choice of material, shortcomings in construction work, traffic loading and environmental impacts.

Asphalt mixtures designed without considering climate impacts may suffer from durability problems caused by the movement of water inside the asphalt mixture. Traffic moving at high speeds over wet pavement trigger pore pressure in the mixture, which consequently accelerates deterioration. The currently used methods, e.g. indirect tensile strength, for testing moisture susceptibility do not subject asphalt samples to cyclic pore pressure or the movement of water within asphalt concrete (AC) during moisture conditioning. In addition, current pavement design methods do not explicitly consider moisture transport or moisture damage in AC and its influence on the functional performance of asphalt mixtures, e.g. stiffness and resistance to cracking. In this work, the moisture damage to AC mixtures was assessed by means of complex modulus testing of dry and moist pore pressure-conditioned asphalt specimens with various mixture compositions. The asphalt mixtures were conditioned with the Moisture Induced Sensitivity Tester (MIST), which, in contrast to current test methods, aims to replicate pore pressure field conditions. The results showed a decline in stiffness modulus and a reduction in elastic properties after MIST conditioning. In addition, the results indicated that binder content and air void content had a significant influence on the reduction in stiffness. To capture the relationship between air void content, binder content and the reduction in stiffness, a relationship was developed and validated with measurements on cores extracted in the field. It was concluded that variations in the mix composition, even when they are within permissible limits, can partly explain why 10% of in situ mixes have a shorter service life than five years.

For assessment of pavement performance, previous studies have proposed relationships for estimating tensile strain at the bottom of asphalt layers from Falling Weight Deflectometer (FWD) surface deflection measurements. Moisture content and temperature are not directly included in these relationships. In practice, when pavement performance is periodically controlled or for comparison between pavement structures, FWD measurements are limited to being conducted during autumn, when temperatures are around 10°C and the unbound layers and subgrade

are usually free from water. In this study, the FWD and strain measurements were conducted at various ground-water levels and temperatures in a full-scale pavement structure. The results revealed that moisture content and temperature had a significant influence on the tensile strain at the bottom of the AC layer. A relationship was proposed for predicting the tensile strain, one that includes moisture content and temperature in the pavement as variables and deflections from FWD measurements. The relationship offers more flexibility for predicting tensile strain at the bottom of the AC layer with FWD measurements at different temperature and moisture conditions for pavement performance assessment. It was stated that environmental conditions should be known and directly included to correctly estimate the tensile strain from the measured FWD deflections according to this study.

Sammanfattning

Tidig nedbrytning av vägar har stor påverkan på underhållsbehovet. Många asfaltbeläggningar i Sverige uppvisar skador redan efter 5 år. Vägar utsätts för både nedbrytning från trafiken och nedbrytning orsakad av klimatinverkan. Påverkan av icke trafik- relaterade parametrar, så som temperatur och fukthalt kan ha stor betydelse på vägens funktion och skador på vägen, exempelvis sprickor, spårbildning, stensläpp och nedbrytning i beläggningsegenskaper t. ex. nedsatt styvhetsmodul. Dessa skador är svåra att karaktärisera och förutsäga, delvis på grund av asfaltens komplexitet och delvis på grund av att dessa skador inte kan kopplas till bara ett fenomen, utan flera, såsom val av material, brister i utförandet, trafikbelastning och klimatpåverkan.

Proportionering av asfaltbeläggningar utan hänsyn till klimatet, t.ex. med hög hålrumshalt och låg bindemedelshalt kan resultera i bristande beständighet med tiden orsakat av vatten inuti asfaltbeläggningen. Upprepade trafikbelastningar på våta beläggningar bidrar till portryck inne i beläggningslagret, vilket kan accelerera nedbrytningen. Nuvarande provningsmetoder för vattenkänslighet av asfaltbeläggningar, utsätter inte asfaltprovkroppar för cykliskt vattentryck under konditionering. Tillräcklig hänsyn tas inte till fuktens skadliga inverkan på asfaltens funktionella egenskaper, så som styvhet och utmattningsegenskaper vid dimensionering av vägkonstruktioner. I denna studie, undersöktes inverkan av portryck på asfaltprovkroppar med varierande hålrumshalt och bindemedelshalt genom att testa asfaltens komplexmodul på både torra och konditionerade provkroppar. Konditioneringen av asfaltprovkropparna utfördes med Moisture Induced Sensitivity Tester (MIST), vilket till skillnad från dagens provningsmetoder, simulerar portryck under cykliska belastningar i fält. Bestämning av komplexmodul på torra och konditionerade provkroppar för att undersöka fuktens skadliga inverkan är ett steg framåt för djupare förståelse av fuktens påverkan på en väg. Resultaten visade på en nedgång i styvhet och reduktion av asfaltens elastiska egenskaper efter konditionering med MIST. Dessutom indikerade resultaten att både bindemedelshalt och hålrumshalt har en signifikant inverkan på reduktionen av asfaltens styvhet. För att beskriva detta förhållande mellan hålrumshalt, bindemedelshalt och reduktion i asfaltens styvhet, togs en formel fram som senare validerades med mätningar på uppborrade provkroppar från en befintlig väg. Slutsatserna indikerar att variationer i sammansättningen, även inom tillåtna gränser, kan vara en bidragande orsak till för tidig nedbrytning av en del beläggningar.

Tidigare studier har föreslagit formler för att estimera dragtöjning i underkant asfalt i samband med tillståndsbedömning av vägkonstruktionens prestanda med tung fallvikt (FWD). Fukthalt och temperatur är inte direkt inkluderade i dessa formler. I praktiken innebär det att tillståndsbedömning och jämförelse mellan konstruktioner begränsas till att utföras under hösten när temperaturen är omkring

10°C och fukthalten i de obundna lagren samt undergrunden är nästintill frånvarande. I denna studie utfördes fallviktsmätningar på fullskaliga vägkonstruktioner vid varierande grundvattennivåer och temperaturer i asfaltbeläggningen. Resultaten visade att både vatten och temperatur har en signifikant inverkan på töjning i underkant asfalt. En formel presenteras för prediktering av töjning beroende av fukthalt, temperatur och deflektioner från fallviktsmätningar. Formeln erbjuder flexibilitet för att prediktera töjning i underkant asfalt mer tekniskt korrekt vid fallviktsmätningar under olika temperatur- och fuktförhållande vid tillståndsbedömning av vägar. Det fastslogs från denna studie att fukthalt och temperatur bör vara kända och inkluderas när dragtöjning i underkant asfalt estimeras, för att kunna uppskatta dragtöjningen från deflektioner erhållna från fallviktsmättningar på ett mer korrekt sätt.

List of appended papers

This thesis is based on the following papers, which will be referred to in the text. The papers are appended at the end of the thesis.

Paper I

Sulejmani, P., Said, S., Agardh, S. and Ahmed, A. (2018). Paper I Moisture Sensitivity of Asphalt Mixtures Using Cycling Pore Pressure Conditioning. Transportation Research Record 1–10 © National Academy of Sciences: Transportation Research Board 2019. Article reuse guidelines: sagepub.com/journals-permissions. doi: 10.1177/0361198118823496journals.sagepub.com/home/trr

Sulejmani, P: Study concept and design with the co-authors in discussion, data collection, analysis and interpretation of results, manuscript writing.

Paper II

Sulejmani, P., Said, S., Agardh, S. and Ahmed, A. (2019). Paper II Impact of Temperature and Moisture on the Tensile Strain of Asphalt Concrete Layers. International Journal of Pavement Engineering, 1-9. doi: http://dx.doi.org/10.1080/10298436.2020.1715404.

Sulejmani, P: Study concept and design with the co-authors in discussion, analysis and interpretation of results, manuscript writing. Technical staff at The Swedish National Road and Transport Research Institute (VTI) carried out the measurements of the test structures and the collection of data.

1 Introduction

1.1 Background

Well-maintained roads are essential for the economic and social development of a country as well for the safety and comfort of road users (European Commission Directorate General Transport, 1997a). In many Nordic countries, the premature failure of pavement is a problem. Premature pavement failure has a large economic impact on maintenance costs. Billions of SEK (1 SEK= € 0.092 in October 2019) are spent on road maintenance each year in Sweden (Swedish Transport Administration, 2014). Normally, it is expected that new asphalt pavement is designed for a service life of at least 20 years for base course asphalt – but except for wearing course, it is estimated in practice that many pavements have a lifespan of only 2 to 4 years in Scandinavian countries (Aurstad et al., 2004). According to a comprehensive survey, 10% of asphalt concrete (AC) layers last less than 5 years before a maintenance action, regardless of the traffic volume on the roads (Lang and Svenson, 2012).

Figure 1 represents a schematic view of premature pavement failures/distresses in Scandinavian countries and the effects of avoiding early distresses (eliminating the 'bump' to the left on the figure), moving the entire curve to the right, which represent sustainable pavements with increased overall pavement life.

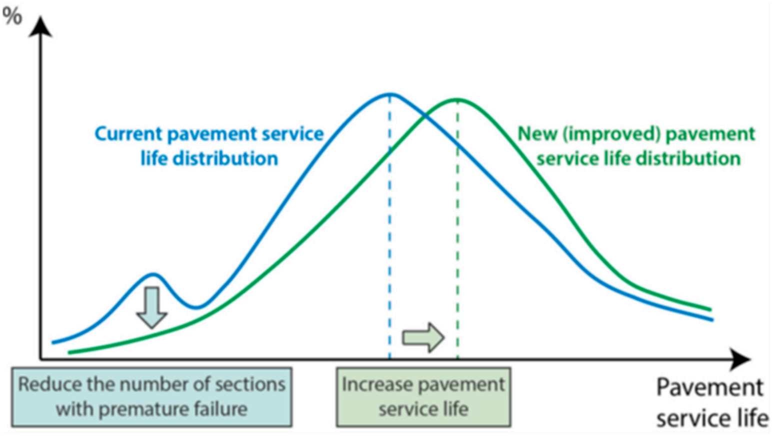

Figure 1. Asphalt pavement life distribution, effects of cutting early failures (Aurstad et al., 2016).

The origin of premature failure or rapid deterioration cannot only be related to traffic loads. Deterioration occurs in synergy with different factors, such as choice of material, shortcomings in construction work, traffic loading and climate impacts (Aurstad et al., 2016). Climate impacts in this case refer to contributors to the deterioration of asphalt pavements, such as low temperature cracking, frost, aging and moisture impact. Frost damage in asphalt layers and frost heave in unbound layers are major contributors to cracks in pavements in Scandinavian countries (Hermansson, 2002). Freeze and thaw cycles represent one of the most important factors in the evolution of frost damage, when zero temperatures may occur up to 1500 times in Sweden (Said, Hermansson and Hakim, 2006; Xu, Guo and Tan, 2015). The other contributors affect and weaken the material properties of AC as well, progressively increasing the damage (Liu et al., 2017; Xu, Guo and Tan, 2015; Caro, 2008; Petersen et al., 1993; Höbeda, 2000; Said, Loorents and Hakim, 2009). The mentioned damage parameters can cause damage on their own, and each may accelerate the deterioration of the others. Nevertheless, moisture damage is considered to be one of the major causes of distresses in asphalt pavements (Grenfell et al., 2014). Water in the pavement structure plays a role, decreasing the service life of pavements and increasing the need for rehabilitative actions (Kandahl and Rickards, 2001).

Water in pavement is undesirable because it contributes to the deterioration of roads. There are three main modes through which water can reach the pavement structure, namely infiltration of surface water, capillary rise of subsurface water, and diffusion of vapour water (Dawson, 2008; Masad, 2007). Mainly, the presence of water in pavement is due to the infiltration of rainwater into deteriorated pavement surfaces through joints or cracks. Once the pavement is cracked, water may infiltrate and accelerate its degradation (Dawson, 2008). Excess water can lower the bearing capacity of the pavement structure and, combined with traffic loads, reduce pavement life (Dawson, 2008). Since road deterioration initiated from water impact occurs in connection with traffic loading, it is difficult to distinguish it from deterioration originating only from traffic loads (Aurstad et al., 2016; Mallick, Pelland and Hugo, 2007). The unbound layers must provide enough support to the bounded part of the pavement that the upper part does not notably deform under traffic loading. Excess moisture content reduces the resilient modulus of the unbound layers, which in turn causes increased tensile strain in the AC layers through poorer support to asphalt bound layers (Said et al., 2011; Roberts et al., 1991). This is an important factor in cold regions, where pavement is commonly saturated during the spring thaw and the stiffness modulus in the granular layers significantly decreases (Huang, 1993; Salour and Erlingsson, 2012; Salour and Erlingsson, 2013). According to a study by Salour and Erlingsson (2014), the strain at the bottom of the AC layer increased from 245 μm/m to 329 μm/m (34% increase) when the groundwater table level was raised from 2.5 meters to 1.0 meters below the road surface. Similarly, Saevarsdottir and Erlingsson (2013) showed that the measured tensile strain at the bottom of the bituminous base significantly increased when the groundwater table was raised from a great depth to 30 cm below the subgrade surface.

Moisture damage of asphalt mixtures is a complex phenomenon, since it is affected by many different factors, namely material properties, mix composition, traffic loading and climate characteristics (Caro, 2008; Airey and Choi, 2002). Commonly accepted theories about moisture damage are that it can emerge from adhesive failure (i.e. loss of adhesion between aggregate and bitumen) and/or cohesive failure (i.e. separation of molecules within the bitumen) (Kiggundu and Roberts, 1988; Terrel and Shute, 1989; Lyne, 2013).

The progress of moisture damage can be divided into short-term and long-term processes. The long-term process refers to moisture diffusion through the mastic, changing the rheological properties and weakening the asphalt binder, which, in time, might result in the debonding of the aggregate–binder interface, which would in turn weaken and promote the stiffness of the asphalt mixture (Varveri, Avgerinopoulos and Scarpas, 2016). The long-term process of moisture damage can make the asphalt mixture fail and accelerate different pavement distress modes (Miller and Bellinger, 2014; Grenfell et al., 2014). The short-term process denotes damage caused by traffic on wet pavements and the occurrence of entrapped water inside the asphalt mixture, causing pumping action and pore pressure inside the asphalt mixture (Varveri et al., 2014; Varveri, Avgerinopoulos and Scarpas, 2016). The pore pressure build-up leads to the opening of new flow paths and to the rupturing of the thin asphalt film; additionally, water may infiltrate the aggregate–binder interface, resulting in stripping and faster deterioration (Kringos and Scarpas, 2005; Kringos, 2008). The action of pore water pressure in the asphalt mixture also leads to a reduction in the dynamic modulus (Varveri, Avgerinopoulos and Scarpas, 2016; Weldegiorgis and Tarefder, 2014; Tarefder, Weldegiorgis and Ahmad, 2014; Dhakal and Ashtiani, 2016; Birgisson, 2005). The short-term process can increase the severity of distresses, such as rutting, raveling, cracking or stripping (Caro, 2008; Airey and Choi, 2002). The most common type of moisture damage is stripping (Caro et al., 2008; Cheng et al., 2003; Kringos et al., 2008). Another mechanism that will intensify stripping caused by traffic on wet pavement is emulsification (Kiggundu and Roberts, 1988; Taylor and Khosla, 1983; St Martin, Cooley Jr and Hainin, 2003).

Further, damage in the bituminous pavement caused by moisture has become increasingly important, since it is expected that precipitation will increase in amount in high-latitude regions (Scandinavian countries), according to Christensen et al. (2007). The potential impacts of climate change on road pavements will vary between regions, in terms of both magnitude and local environmental conditions (Arvidsson et al., 2012).

1.2 Assessment of pavement performance

The two most important environmental factors that influence pavement performance are temperature and water (Qiao et al., 2013; Zuo, Drumm and Meier, 2007). To maintain durable pavements via deflection testing, the Falling Weight Deflectometer (FWD) device is commonly used for the assessment of pavement conditions. The deflections obtained from FWD measurements may be used to estimate stresses and strains induced in the structure by a wheel load (European Commission Directorate General Transport, 1997b; Park and Kim, 2003; Kim, 2001). FWD measurements are frequently used to calculate strains in the bottom surface of the asphalt layer in order to determine the fatigue life of the pavement with respect to bottom-up cracking (Park and Kim, 2003). Previous studies have proposed relationships for estimating tensile strain at the bottom of the asphalt layer from FWD surface deflection measurements (Xu, Ranjithan and Kim, 2002; Jansson, 1994; Swedish Transport Administration, 2012b). These relationships assume that the effects of environmental conditions are reflected in the deflections from FWD measurements. Thus, temperature and moisture content parameters are not directly included in these relationships. Also, these relationships have been developed based on theoretical calculations of surface deflections and horizontal strain at the bottom of the asphalt layer using a multilayer elastic theory (Xu, Ranjithan and Kim, 2002; Jansson, 1994). Differences in the underground water table and moisture content in the unbound layers are often unknown when the assessment of pavement conditions with FWD measurements are performed, which in turn causes variations in the results due to measurement difficulties (Swedish Transport Administation, 2012a).

1.3 Design of durable pavements

The influence of the water susceptibility of the asphalt mixture is typically not adequately considered in pavement design. To design durable pavements, the stiffness modulus of AC and the tensile strain at the bottom of the AC layer are two parameters used for mechanistic- empirical design models when estimating the service life of the pavement (Huang, 1993). Both of these parameters are influenced by moisture in the pavement (Dhakal and Ashtiani, 2016; Tarefder, Weldegiorgis and Ahmad, 2014; Weldegiorgis and Tarefder, 2014).

Usually, two responses are considered and controlled when pavements are designed, namely the tensile strain at the bottom of the bituminous layer and the compressive stress or strain at the top of the subgrade (Vejdirektoratet, 2017; Huang, 1993). The effect of temperature and moisture is considered in the design of methods. Temperature affects mainly the modulus of bituminous layers, whereas the effect of moisture is significant on the subgrade and granular layers (Basma and Al-Suleiman, 1991). Temperature is representatively considered depending on the season (Pereira and Pais, 2017). An example of how weather data can be used to describe temperature variations in AC layers and in pavement design is presented by Lindelöf, Said and Ahmed (2019).

Currently used pavement design methods do not explicitly consider moisture transport or moisture damage in the AC. Moisture damage in asphalt mixes is considered mostly during the mix design, which is valid only during the design and does not provide information for the entire pavement life. Implicitly, moisture content is accounted for in the unbound layers through reduced elastic moduli for seasons subjected to high water content (PIARC, 2012; Hansson, 2005). One of the main criticisms of current methods is that they use the initial properties of the materials to predict performance across the entire life span of pavements (Pereira and Pais, 2017).

Pavement design in Sweden is performed using a programme called PMS-Object (Pavement Management System). PMS-Object is a mechanistic-empirical design tool that limits subgrade rutting and fatigue cracking at the bottom of the asphalt layer. The design method considers seasonal and regional climate variations by dividing a country into five climate zones, as illustrated for Sweden in Figure 2. Each climate zone has four or six sub-seasons, as shown in Table 2. Temperature effects are accounted for in AC layers using different stiffness elastic moduli E-modulus, corresponding to a number of days at a specific temperature and depending on the specific combination of climate zone and sub-season. The effect of moisture is taken into account in the unbound layers. For wet seasons, the elastic moduli are reduced for the unbounded layers (Swedish Transport Administation, 2011).

Figure 2. Climatic zones in Sweden (Swedish Transport Administation, 2011).

Table 2. Length of climatic period (days/year) (Swedish Transport Administation, 2011)

	Climatic zone				
	1	**2**	**3**	**4**	**5**
Winter	49	80	121	151	166
Thaw in winter	10	10			
Thaw period	15	31	45	61	91
Late spring	46	15			
Summer	153	153	123	77	47
Autumn	92	76	76	76	61

In order to design sustainable pavements, Pereira and Pais (2017) suggested that current design models can be improved by implementing a climatic databank that contains temperature profile, moisture profile and ageing profile, with the aim of capturing climate change and evaluating its impact on pavement performance over the entire pavement life span. Pereira and Pais (2017) stressed that one of the requirements of this new pavement design method would be to address, separately, its main components: geometry, traffic, climate conditions, materials and the design system, including response and performance models.

Figure 3 shows the flow chart of a typical M-E pavement design method (modified from Ahmed, 2014) with emphasis on integrating temperature profile, moisture profile and ageing in the foundation and in the material properties. Climate influences the material properties of the different layers and profoundly affects the deterioration analysis process. A structural pavement design programme based on mechanistic-empirical principles could be used to assess the effects of changes in climatic conditions on the performance of pavement structures.

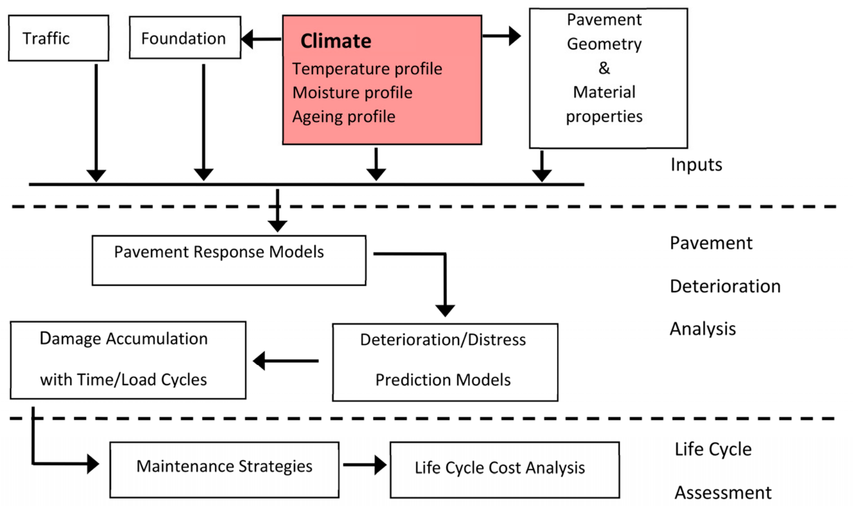

Figure 3. flow chart of a typical M-E pavement design methods(modified from Ahmed, 2014) with emphasis on integrating temperature profile, moisture profile and ageing in the foundation and in the material properties.

1.4 Design of durable asphalt mixtures

To design durable asphalt mixtures, it is important to consider those properties of the mixtures that can resist moisture damage. The most common method employed against water sensitivity is the use of antistripping additives (Aksoy et al., 2005). The resistance of an asphalt mixture to moisture damage can also be improved by increasing the binder content of the mixture and thus increasing binder film thickness, which will in turn create a thicker barrier to prevent water from reaching the bitumen–aggregate interface and thus minimising the risk of adhesive failure. Reducing the air void content of the compacted material and limiting the movement of water within the asphalt mixture will also reduce the risk of moisture damage (Airey, 2008). Adequate mix design can prevent premature failure of asphalt pavements (Airey, 2008). Mixture properties, such as permeability, air voids and asphalt film thickness, are suggested to be the most important factors in affecting the amount of moisture damage (Solaimanian, Kennedy and Elmore, 1993). Depending on how the asphalt mixture is composed, stiffness will decrease during prolonged exposure to moisture, which will be accelerated by traffic loads on wet pavements (Rahman et al., 2017). In addition, crack initiation and crack propagation through a pavement, depending on the composition of the asphalt mixture, are also affected by moisture (Chen, Lin and Young, 2004).

1.4.1 Air void content

Numerous studies have been carried out to determine the potential relationship between air voids, permeability, aggregate gradation and moisture susceptibility of mixtures with the aim of finding an air void content design that will minimise moisture damage (Caro, 2008; Epps, 2000). Tarefder and Ahmad (2014) concluded from their study that moisture damage is related to permeability. At an air void content above 6–8%, the permeability of the asphalt mixture will increase rapidly and it becomes possible for voids to connect, which would in turn result in a considerable degree of moisture damage (Dawson, 2008). Less damage occurs for open-graded mixtures, in which air void levels of 15%–25% allow water to drain (Caro, 2008). Castelblanco, Birgisson and Masad (2005) and Chen, Lin and Young (2004) proposed the use of three categories to classify air voids depending on the asphalt mixture's ability to withstand moisture damage, namely effective (free drainage), semi-effective (intermediate) and impermeable (low air void content). Birgisson (2005) suggested that there is a range of average air void sizes for which moisture damage reaches its maximum extent, denoted as the pessimum air void size (between 0.8 mm-1.4 mm).

Nevertheless, total air voids do not provide a comprehensive measure of moisture damage, since there is evidence that mixtures with a low percentage of air voids are damaged by the infiltration of water (El Hussein, El Halim and Kennepohl, 1993). Other research has also demonstrated that moisture damage is not only related to the percentage of air void content but also to the shape, size and distribution within the mixture (Masad et al., 1999). Therefore, X-ray and image analysis have been used to fully characterise the air void structure in terms of size, distribution, connectivity and tortuosity of the flow path in earlier studies (Al Omari, 2005; Masad et al., 2005; Arambula, Masad and Martin, 2007) These parameters are, according to Caro (2008), more suitable for understanding modes of transport and their relationship to moisture damage.

1.4.2 Binder content and types

Researchers have shown that decreases in asphalt binder content implemented to satisfy the rutting properties of asphalt mixtures, which are associated with increases in traffic, may be one of the factors affecting the moisture susceptibility of asphalt pavement (Aurstad et al., 2004; Epps, 2000). Uppu et al. (2015) concluded that moisture damage increases as the binder content decreases. Sengoz and Agar (2007) studied the relationship between asphalt film thicknesses and moisture damage in AC. The objective of the study was to determine at which thickness of asphalt film does the lowest level of moisture damage occur. A good correlation between asphalt film thickness and moisture damage, with a determination coefficient of $R^2= 0.99$, revealed that the optimum range of asphalt film thickness needed to prevent the detrimental effect of moisture is between 9.5 and 10.5 µm.

Varveri, Avgerinopoulos and Scarpas (2016) studied the moisture damage susceptibility of different binder types using bath immersion (long-term moisture damage process) and pore pressure (short-term) applications. The results indicated that mixtures with unmodified binders are more prone to moisture damage compared to mixtures with modified binders (Styrene–Butadiene–Styrene SBS-modified Cariphalte XS 60/90 and Sealoflex 5-50 (PA) bitumen 45/80), regardless of which test was used. However, short-term and long-term induced moisture damage have diverse influences on the asphalt mixtures depending on the grade of the binder. The results indicated that bath conditioning caused a greater reduction in the strength of mixtures with softer binders but had a relatively minor effect on mixtures with harder binders. On the other hand, the short-term effects from the pore pressure application showed the opposite trend.

1.5 Test methods to evaluate moisture damage

Several test methods exist to evaluate the resistance of pavement to moisture damage, but none are considerably popular. The current methods for testing the moisture sensitivity of asphalt mixtures are largely based on empirical knowledge utilised in mix design and do not take all the effects of traffic and climate (Doré and

Zubeck, 2009) into account. The current methods used for testing moisture susceptibility, AASHTO T283-7 (2008) and European standards EN 12697-12 (2008), include the preparation of two sets of samples. One set is conditioned dry to the testing temperature. The other set undergoes either immersion or more severe handling, such as vacuum saturation and freeze–thaw cycling. Moisture susceptibility is then evaluated by a ratio describing strength between the dry and wet samples determined from indirect tensile strain. Although a minimum indirect tensile strength ratio (ITSR) of 75% to 80% is generally specified as the passing limit for a mixture, there may be local deviations (Doré and Zubeck, 2009).

The Moisture Induced Sensitivity Tester (MIST) is a relatively new test for conditioning AC samples for evaluating moisture susceptibility of AC by simulating pore pressure, film rupture, and hydraulic scoring. The MIST has been developed to quickly (< 24h) simulate the conditions of repeated generation of pore pressure in a saturated pavement under traffic load. MIST replicates the action of traffic on wet pavement by putting on and taking away high pressure from AC specimens, which is kept in the water maintained at constant temperature (Buchanan et al. 2004). The MIST equipment includes a hydraulic pump and piston mechanism, which cyclically adds and relives pressure inside the chamber. The water is forced out of and below the AC specimen surface and downward in the chamber. Next, by applying vacuum, water is pulled back into the chamber and into AC specimen. Each cycle of loading involves pushing water into the sample and pulling the water out, just as in the field when a tire moves over a wet pavement. To begin the test, an AC specimen is placed on a pedestal inside the conditioning chamber and filled with water. The chamber is then closed with a lid. Water inside the bath is heated to the desired temperature with an immersion heater before the pore pressure cycles starts. Then, the water is pushed and pulled through the specimen, thus, creating pressure cycles at the chosen pressure. Moreover, using MIST it is possible to conduct moisture conditioning at different temperatures, pressures, and number of cycles. This system is capable of operating at higher than normal temperatures and creating pore pressure within a compacted asphalt mixture to achieve an acceleration of the effects that a mixture would experience over time from traffic at normal temperatures and conditions (ASTM D7878/D7870M-13, 2013)

In contrast to ITSR, a dynamic modulus test can be performed on the wet- and dry-conditioned samples to investigate moisture damage over a wider range of loading frequencies and temperatures. The initial stiffness of dry specimens can be used as references for the calculation of the fatigue life of both dry and wet specimens. The use of indirect tensile tests and Moisture Induced Sensitivity Tester (MIST) conditioning to investigate moisture damage can, therefore, be used as a step towards a mechanistic understanding of moisture damage in asphalt (Weldegiorgis and Tarefder, 2014).

These two methods, AASHTO-T283-7 and SS-EN 12697-12, do not subject asphalt samples to cyclic water pressure or dynamic movement of water during moisture conditioning. In contrast to current standard methods, MIST attempts to simulate the action of pore pressure caused by tire pressure on wet pavement (ASTM D7878/D7870M-13, 2013). By changing the parameters for the moisture conditioning system (i.e. pressure, temperature and number of cycles), existing field conditions can be simulated. Weldegiorgis and Tarefder (2014) recommended increasing conditioning pressures and cycles for high volume roads. Moreover, Varveri, Avgerinopoulos and Scarpas (2016) recommended the development of a specification for testing asphalt mixture sensitivity to moisture by including the effects from short-term moisture damage (pore pressure conditioning) in the evaluation procedure.

1.6 Research gap

The properties of asphalt mixtures are generally optimised based on traffic loading and characterised with respect to temperature. The temperature susceptibility of AC with regard to stiffness has been studied more thoroughly. Advanced pavement design programmes take into account seasonal temperature fluctuations. Moisture susceptibility has, on the other hand, been treated less comprehensively. Accordingly, mixture compositions with decreased binder content aimed at mitigating the risk of permanent deformation have not kept pace with climate impacts, which will eventually lead to durability problems. There is a need for research to evaluate the expected challenges related to climate impact, e.g. influence of moisture content on the functional properties of AC, such as stiffness modulus and resistance to fatigue cracking. Due to climate change, the modes may change and the damage may intensify via increased temperatures and moisture content. The presence of moisture in the pavement and its yearly variations must be taken into consideration to a greater extent while pavement is being designed.

Simulating prevalent loading conditions and climate conditions in the laboratory can be used to evaluate the stiffness and fatigue properties of asphalt mixtures from a durability angle and can be incorporated in the pavement design programme. A durability model for flexible pavement should be used to predict the service life of the pavement, and the AC mix design should be based on functional properties considering local climatic conditions. Ideally, the expected outcome of studying the impact of climate on the functional properties of asphalt mixtures will be useful in terms of reduced maintenance costs by improving pavement design programmes and by developing a mix design that exhibits increased sustainability.

Moisture in the unbound layers is typically unknown when assessments of pavement conditions with FWD or Traffic Speed Deflectometer (TSD) measurements are performed. Likewise, the moisture content in pavement is usually not incorporated when estimating tensile strain relationships at the bottom of bituminous layers. This, in practice, makes it difficult to compare measurements conducted in various seasons and climatic conditions. In addition, incorporating moisture content and temperature in the relationships for estimating tensile strain at the bottom of the AC layer has the potential to yield a more technically correct estimation of AC response.

Ideally, better knowledge of pavement performance under the influence of water will improve the mixture design of asphalt mixtures, the structural design of pavement and the assessment of pavement as well as increasing the service life of roads. Therefore, to design a durable pavement, reducing moisture damage is a key objective.

2 Aim and Scope

The aim of this licentiate thesis is to study the effect of moisture and temperature on the deterioration of flexible road structures, i.e. degradation of the functional properties of pavement, such as the stiffness modulus and resistance to fatigue cracking under the influence of climate variation.

The activities discussed within this thesis were aimed at developing new knowledge about climatic impacts (moisture and temperature) as well as how such knowledge can be incorporated in mix design and pavement design, as well as in the assessment of existing pavement to improve the quality of asphalt, thereby avoiding early deterioration and achieving longer service life.

Laboratory testing of various asphalt mixtures was performed to simulate the prevalent loading and climate conditions of asphalt pavements. Of particular interest was the simulation of the action of pore pressure caused by tire pressure on wet pavement. This was done by using the MIST. The stiffness of the asphalt mixture, as a fundamental property, was assessed on dry and wet moisture-conditioned AC specimens to evaluate the influence of repeated pore pressure conditioning.

The influence of moisture and temperature on pavement performance was studied by means of instrumented test pavement structures. In this part of the study, the tensile strain at the bottom of the asphalt layer at various levels of pavement temperature and groundwater levels was evaluated.

Figure 4 shows a schematic diagram of the work: the problems, knowledge gaps and the methods used.

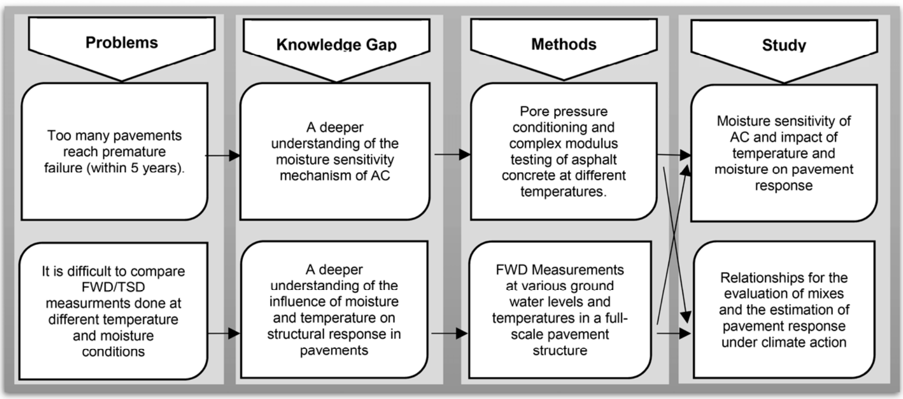

Figure 4. Research framework. Schematic flow of the research activities in the thesis.

3 Studies

The following sections present a short summary of the two papers produced as a result of this thesis work. The first paper deals with the evaluation of the moisture sensitivity of AC mixtures using laboratory test procedures (Paper I appended to this thesis). The second paper assesses the influence of temperature and moisture on the performance of test pavement structures (Paper II appended to this thesis).

3.1 Study 1: Moisture Sensitivity of Asphalt Mixtures Using Cyclic Pore Pressure Conditioning

3.1.1 Background

One of the major causes of premature failure in asphalt pavements is moisture damage. Asphalt mixtures designed with an inadequate focus on moisture damage may suffer from durability problems caused by the movement of water inside the asphalt mixture. The current methods used for testing moisture susceptibility, AASHTO-T283-7 and SS-EN 12697-12, do not subject asphalt samples to cyclic water pressure or to the dynamic movement of water during moisture conditioning.

3.1.2 Aim of study

The objective of the study was to assess the influence of mixture composition, with varying binder content and air void content, on moisture damage.

3.1.3 Method

Bituminous base course AG16 100/150, according to Swedish code (Trafikverket, 2011), was selected for this study, with a maximum aggregate size of 16 mm. Asphalt mixtures with varying binder content and air void content were manufactured. These asphalt mixes were designated Mix A, Mix B and Mix C. The binder content for the three mixes was 4.4%, 4.7% and 5.1%, respectively. The air void content for Mix A was 6.6%, for Mix B, 6.0% and for Mix C, 3.2%.

MIST was used to condition the asphalt mixtures for evaluating moisture damage. The parameters for the moisture conditioning system (i.e. pressure, temperature and number of cycles) were 275 kPa, 40°C and 3,500 cycles, respectively, in accordance with ASTM T Standard D7870/ D7870M (ASTM D7878/D7870M-13, 2013).

To determine the moisture damage induced by cyclic pore pressure over a wider range of loading frequencies and temperatures, dynamic modulus tests were conducted before and after conditioning at various temperatures and frequencies. The dynamic modulus tests were conducted under sinusoidal loading using the cyclic indirect tensile test (CITT), according to EN 12697-26 (2012). Three specimens per mix were tested at three different temperatures (1°C, 10°C and 20°C) and seven frequencies (16, 8, 4, 1, 0.5, 0.10, 0.05 Hz) for both dry and MIST-conditioned samples.

3.1.4 Results

Figure 5, a–c, illustrates the master curves of the dynamic moduli before and after mix conditioning for three different mixes: Mix A, Mix B and Mix C.

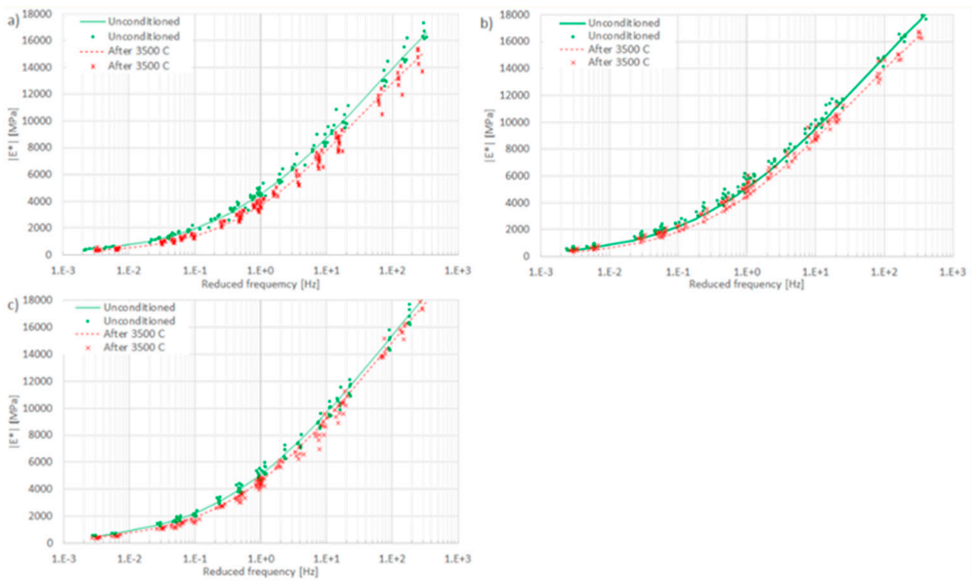

Figure 5. Master curves for phase angle for (a) Mix A: 6.6%/4.4%, (b) Mix B: 6.0%/4.7% and (c) Mix C: 3.2%/5.1%, before and after pore pressure conditioning.

The overall average decrease in the dynamic modulus was found to be 12% after 3,500 cycles of pore pressure conditioning for the three mixtures. This indicates that cyclic pore pressure conditioning caused moisture damage to the asphalt mixture over a wide range of frequencies and temperatures. The results also revealed that binder content and air void content have significant influence on |E*| reduction after conditioning the samples with 3,500 pore pressure cycles. In this regard, the mixture with the lowest air void content and highest binder content demonstrated the best resistance to moisture damage.

The master curve for the phase angle of dry samples was compared with the master curve for the phase angle of conditioned samples (see Figure 6, a–c).

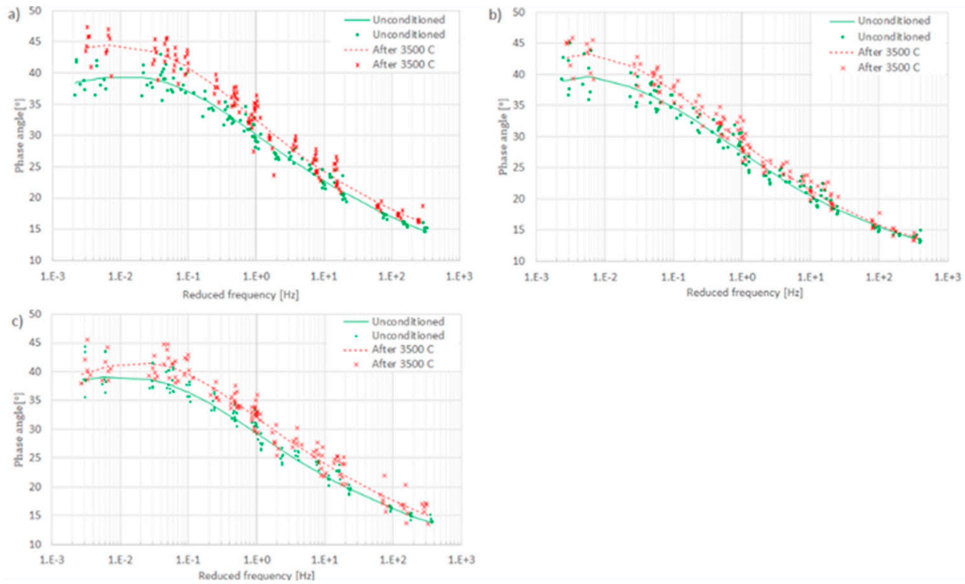

Figure 6. Master curves for phase angle for (a) Mix A: 6.6%/4.4%, (b) Mix B: 6.0%/4.7% and (c) Mix C: 3.2%/5.1%, before and after pore pressure conditioning.

After 3,500 cycles, the phase angles increased the most for Mix A, the mix with the lowest binder content and highest air void content, and least for Mix C, the mix with the highest binder content and lowest air void content. Overall, the results from phase angle diagrams indicate that the asphalt mixture results in a higher phase angle after pore pressure conditioning, which in turn influences the functional properties of AC.

To capture the effect of binder content, air void content and pore pressure conditioning on the reduction of |E*| as percentages, a multiple linear regression analysis was conducted based on the specimens used in this study. Equation 1 is a linear function of the effect of binder content and air void content on the degradation of the asphalt mixture

$$\Delta|E^*| = -0.8 * B + 2.5 * A \quad (1)$$

where Δ|E*| = reduction of dynamic modulus (%), B = binder content (%) (4.25%–5.16%) and A = air void content (%) (3.0%–7.0%).

The relationship was validated with measurements of cores extracted in the field with an air void of 3.4%, 5.1% and 13.1%. The measured and predicted values of |E*| reduction using Equation 6 for laboratory-manufactured specimens and field cores are shown in Figure 7.

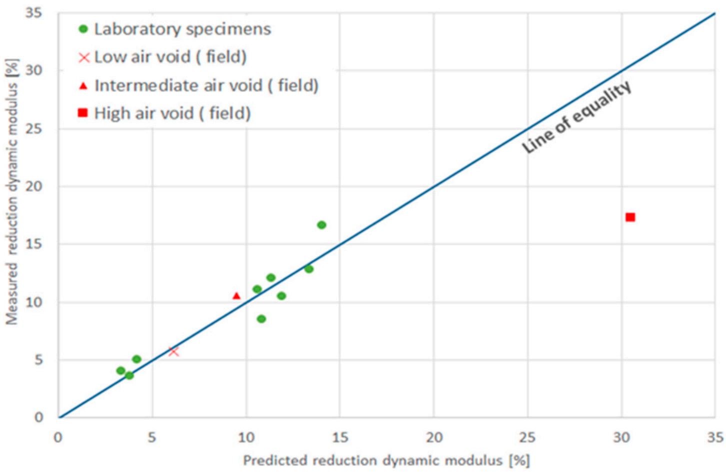

Figure 7. Measured and predicted values of reduction in dynamic modulus after moisture conditioning of laboratory specimens verified with field specimens.

Field specimens with moderate air void content (3.4% and 5.1%) showed good agreement between the predicted and measured reduction in dynamic moduli. However, the specimen with high air void content (13.1%) was overestimated.

3.1.5 Conclusions

The following conclusions can be drawn from the study:

- A relationship was developed between air void content and binder content under the influence of pore pressure cycles and the reduction of the dynamic modulus |E*|. The relationship was verified with a limited number of measurements in cores from a field study.
- Cycling pore pressure conditioning results in decreases in dynamic moduli and increases in phases angles, indicating the weakening of mixtures.

3.2 Study 2: Impact of Temperature and Moisture on the Tensile Strain of Asphalt Concrete Layers

3.2.1 Background

Moisture in unbound layers and temperature in asphalt layers affect the structural response of pavements, such as the tensile strain at the bottom of AC layers. Previous studies have proposed relationships for estimating tensile strain at the bottom of asphalt layers from FWD surface deflection measurements. These relationships have been developed based on theoretical calculations of strains and surface deflections.

3.2.2 Aim of study

The main objective of this study was to evaluate these relationships using measured FWD deflections and tensile strains at the bottom of the asphalt layers. In addition, this study sought to develop new relationships for predicting tensile strain with regard to temperature variations and groundwater levels in the pavement structure using deflections from FWD measurements.

3.2.3 Method

Three indoor pavement structures were built at VTI (The Swedish National Road and Transport Research Institute) to study the effect of moisture and temperature on the structural responses of the pavement structure to loading. The structures were denoted as SE 14, SE 18 and SE 20.

The FWD measurements were conducted at various temperatures and groundwater levels in the pavement structure. Table 3 summarises the different environmental conditions for the measurements performed.

Table 3. Temperature and groundwater level used in the study

Environmental Conditions	SE 14					SE 18			SE 20	
Temperature [°C]	5.5	9.0	18.5	10.8	11.3	4.9	10.3	17.4	0.9	6.6
GWT (below subgrade surface) [cm]	>300	>300	40	3	>300	>300	>300	>300	>300	>300
Volumetric water content (22.5 cm below subgrade surface) [%]	8.2	8.3	8.3	20.9	30.1	16.6	16.1	16.0	8.0	8.0

The structures were instrumented to measure strain at the bottom of the bituminous layer, temperature in the AC layer and volumetric water content in the subgrade. A schematic overview of the three structures and the instruments used in this study are shown in Figure 8.

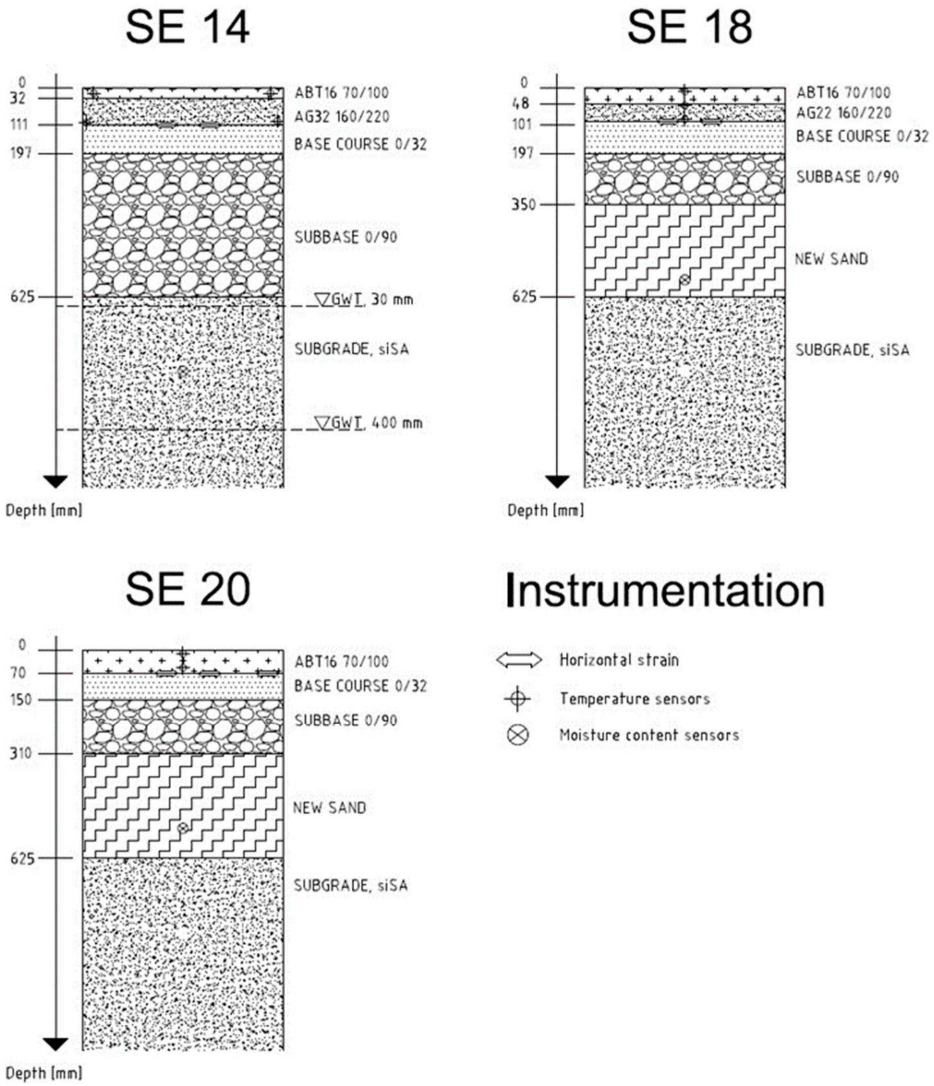

Figure 8. A cross-section of pavement structures SE14, SE18 and SE20 as well as the vertical location of the instrumentation.

3.2.4 Results

The deflection basins illustrated that temperature merely influenced the AC layers, whereas changes in the groundwater table affected the outer part of the deflection basins, which indicates a weakened subgrade. The results revealed that the deflection and measured tensile strains at the bottom of the AC layer considerably increased as the groundwater table level was raised and the pavement temperature was increased. A change in temperature from 10°C to 18°C increased the vertical deflection by 12% and the measured tensile strain by 15% at the loading centre. Moreover, changes in the groundwater level from a great depth to 3 cm below the subgrade surface increased the vertical deflection by 43% and the measured strains by 18% at the loading centre.

Previous studies have proposed relationships for estimating tensile strain at the bottom of the asphalt layer from FWD surface deflections measurements. This study showed that the strains estimated using these relationships have poor agreement with the measured strains for the structures, especially in conditions with excess moisture content in the subgrade.

Multiple linear regression analysis was performed between the measured asphalt strain (dependent variable) and deflections, and asphalt layer thickness, temperature in the AC and moisture content at a depth 22.5 cm below the subgrade surface were tested as independent variables.

A new relationship, Equation (2), was proposed based on the ANOVA analysis conducted in this study to estimate the horizontal strain at the bottom of an AC layer based on the measured FWD deflections, strains, temperatures and moisture content.

$$\boldsymbol{\varepsilon_{ac} = 199.25 + 5.31 * T - 5.50 * v + 0.69 * D_0 - 1.62 * D_{300} + 3.39 * D_{900}} \quad (2)$$

where ε_{ac} = is the measured tensile strain at the bottom of the AC [μ strain], T = is temperature (°C), v = the volume water content at a depth 22.5 cm below the subgrade surface [%] and D_0, D_{300}, D_{900} represent the deflection at a horizontal distance from the load 0, 300 and 900 mm [μm].

The ANOVA analysis showed that all independent variables selected in this equation have a significant effect on the predicted strain at the bottom of the AC layer.

The estimated strains using Equation (2) were compared to the measured strains (see Figure 9).

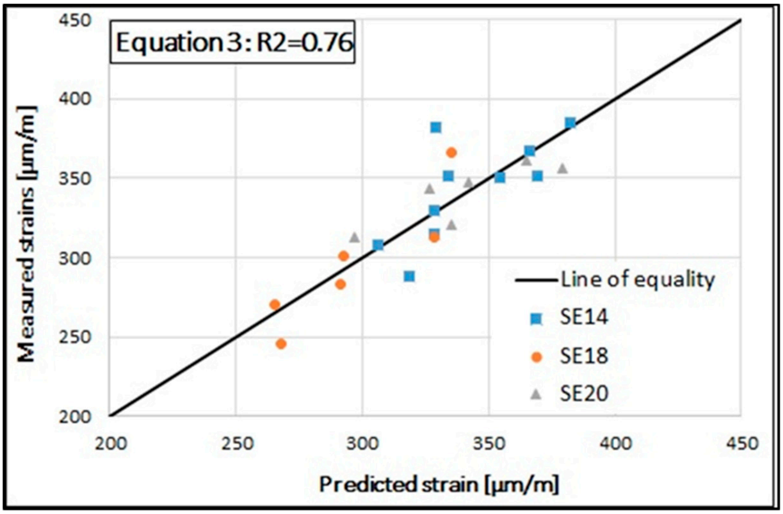

Figure 9. Measured and predicted values of horizontal strain at the bottom of the asphalt layer using Equation (2).

The relationship (Equation (2)) with moisture content as an independent variable showed better accuracy in terms of the measured strain compared to current relationships. According to this study, it can be stated that environmental conditions should be directly included to correctly estimate the tensile strain from the measured FWD deflections.

3.2.5 Conclusions

The following conclusions can be drawn from the study:

- Temperature and moisture content significantly contribute to explaining the strain at the bottom of the AC layer.
- An enhanced relationship was developed between temperature, moisture content surface deflection measurements and the tensile strain at the bottom of the asphalt layer. The relationship can be useful in the evaluation of the influence of environmental parameters at the strain level at the bottom of the AC layer.

4 Discussion

Climate models show that we are moving towards an era of higher temperatures, warmer summers and milder winters, scenarios in which intense precipitation increases may lead to greater moisture damage of AC and reduced bearing capacity of the unbounded layers. Moreover, frequent intense rainfalls may result in higher groundwater levels, which will have a direct influence on the performance of road structures with reduced structural strength and reduced bearing capacity. According to PIARC (2012), it is expected that short- and long-term effects of climate change may require the increased maintenance and reconstruction of roads, which will consequently increase the costs for road maintenance.

The activities discussed within this thesis were performed to increase knowledge about climate impacts (moisture and temperature) as well as to determine how such knowledge can be incorporated in mix and pavement design. The intention was to study the influence of moisture on AC in the context of main deterioration phenomena, i.e. decreases of the stiffness of AC. The asphalt specimens were conditioned via pore pressure conditioning, which aims to replicate actual field conditions. Dynamic modulus tests were performed on the wet- and dry-conditioned samples to investigate moisture damage over a wide range of loading frequencies and temperatures. When it comes to the method used, the MIST and complex modulus testing methods were selected because of their advantages compared with other methods, AASHTO-T283-7 and SS-EN 12697-12, for better replicating actual field conditions to evaluate the influence of repeated pore pressure conditioning. The major advantage of using a complex modulus for evaluating the moisture sensitivity of AC, instead of using ITSR, is that a complex modulus can be performed on the same specimen in both dry and wet conditions. On the other hand, MIST conditioning is a relatively new test method, one which therefore needs additional testing to validate the findings.

The results revealed that pore pressure conditioning influenced the dynamic modulus of the AC. Similar findings have been reported in other studies (Weldegiorgis and Tarefder, 2014; Tarefder, Weldegiorgis and Ahmad, 2014; Dhakal and Ashtiani, 2016). In addition, the results showed increases in phase angles after pore pressure conditioning, indicating increases in viscosity and decreases in the elastic characteristics of the AC. These results from this study are consistent with those of a study conducted by Cardona (2016), in which it was observed that the phase angle increased after conditioning the samples in a water bath for 168 hours at 60°C. The maximum differences in the phase angle between the dry and conditioned samples were higher in this study compared with those in the study by Cardona (2016). This likely indicates that pore pressure conditioning is a more severe method for simulating the impact of moisture damage compared with conditioning the samples solely in a water bath. It is therefore recommended that specification for testing AC sensitivity should also include the effect of pore pressure conditioning, which is in agreement with Varveri, Avgerinopoulos and Scarpas (2016) (2016).

The bituminous base course AG16 100/150, according to Swedish code, was selected for this study. The advantage of using a base course is that the Swedish code allows for a wide range of bitumen content and air void content. Additional tests on wear course would be valuable, too. In this study, AC with varying binder content and air void content within the permitted range of the Swedish specification showed considerable differences in terms of the ability to resist moisture damage. Airey (2008) reported similar results, where small differences in mix composition resulted in significant differences in the ability of the asphalt mixture to resist moisture susceptibility. It has been shown in this thesis that the moisture sensitivity of AC can be enhanced by appropriate binder and air void contents, which are significant in preventing a decrease of $|E^*|$ after pore pressure conditioning. A relationship was developed to determine $|E^*|$ reduction based on binder content and air void content.

This relationship was verified with measurements from cored specimens reported by Rahman et al. (2017), which showed good accuracy for low to intermediate air void content according to Swedish Transport Administration requirements; however, the accuracy was poor when the air void content was higher and outside these requirements.

The results from this study may provide knowledge that can be implemented as functional requirements in relevant guidelines. It is concluded that variations in the mix composition, which could in practice be greater than the allowed limits, may partly explain why 10% of in situ mixes have a shorter service life than 5 years. The use of indirect tensile stiffness/dynamic modulus tests and pore pressure conditioning to investigate moisture damage is a positive step towards understanding the mechanism of moisture damage in AC. The influence of the water susceptibility of the asphalt mixture should be considered in the mix and pavement design to improve long-term pavement performance. Dry conditions for AC are generally assumed in today's M-E pavement design programme. Water susceptibility of the AC is only considered to a limited extent on the functional performance. This is a step forward compared with current practice, in which moisture sensitivity is only considered in the mix design phase.

In the evaluation of existing flexible pavement, three full-scale test sections were studied in this work at different water table levels and temperatures. Studying full-scale test sections in this work demonstrated that the moisture content in the subgrade significantly affects the tensile strain at the bottom of the AC layer, which in turn demonstrates that the moisture content in the pavement should be known when existing pavements are assessed for rehabilitation and maintenance strategies. Similar findings have been reported in other studies (Saevarsdottir and Erlingsson, 2013; Salour and Erlingsson, 2014). Increased moisture content in the unbound layers and subgrade may cause increased strains in the AC layers through poorer support to asphalt bound layers (Said et al., 2011; Roberts et al., 1991). In addition, it was revealed that temperature mainly affects the FWD deflections from the loading centre to a distance of 300 mm, which is in agreement with earlier studies reported by El-Maaty (2017).

According to this study, climate conditions should be directly included to correctly estimate tensile strain from the measured FWD deflections. A relationship was proposed to estimate the horizontal strain at the bottom of the AC layer based on the measured FWD deflections, tensile strain at the bottom of AC layers, pavement temperatures and moisture content in unbound layers. The relationship showed good accuracy with the measured strain. The proposed relationship offers a more accurate prediction of tensile strain at the bottom of the AC layer using FWD measurements at different temperatures and moisture conditions. The outcome of this study may help generate a more rational and meaningful procedure for the evaluation of pavement structure from a durability angle. The incorporation of climate impact for the assessment of the condition of flexible pavements would enhance the prediction of the service life of pavements, which would in turn greatly contribute to proper rehabilitation and maintenance strategies for highway agencies. The knowledge gained will also help in reducing maintenance costs and improving performance. Furthermore, validation of the developed relationship in actual field conditions is also required to ensure the reliability of the model.

The ANOVA analysis showed that all independent variables selected in the proposed equation (Equation 2) have a significant effect on the predicted strain at the bottom of the AC layer. Surprisingly, from the multiple linear regression analysis, the thickness of the AC layer did not give yield any significant contribution to the estimation of the strain at the bottom of the AC layer. As noted earlier, AC layer thickness is an important factor when the strain at the bottom of the layer is predicted (Ullidtz, 1998; Said et al., 2011; Jansson, 1994). However, the AC thickness was found to be insignificant in this work. This may be because of the relatively narrow range of AC layer thicknesses (70–110 mm) for the structures used in this study, which are in the range of typical Swedish structures (Said et al., 2011).

Regarding the test method used, the FWD measurements were performed using KUAB 50 kN equipment, corresponding to a standard axel load of 100 kN. The behaviour of pavement structures under external traffic loading is very complex and depends on many factors, such as loading characteristics, layer thicknesses and their material properties, as well as the environment. Unlike pavements under real traffic scenarios, FWD measurements imply unwanted limitations, such as the ability to predict the behaviour of the structure under dynamic loading conditions. An accelerated load test could be used to investigate the response behaviour and performance under controlled climate conditions. Accelerated load tests, thus, cannot simulate actual field conditions, which is required to ensure the reliability of the model. Yet, FWD testing is the most common way to assess existing road structures.

Regardless of the test methods used, moisture was found to have a major impact on AC deterioration. From this study, it was concluded that the overall average decrease in the dynamic modulus was 12% after 3,500 cycles of pore pressure conditioning. Moreover, it was established that changes in the groundwater level from a higher depth to 3 cm below the subgrade surface increased the measured strains by 18% at the loading centre. The influence of the groundwater table level and the decrease of the dynamic modulus after pore pressure conditioning on the remaining fatigue life of the pavement structure was investigated. One of the two critical strains that are traditionally considered for pavement structure evaluation, namely the horizontal strain at the bottom of the AC layer, was used with PMS-Object in accordance with the Swedish Transport Administration design code (Swedish Transport Administration, 2011). Three structures were selected, consisting of 500-mm unbound layers and AC layers ranging between 45 and 160 mm. The E-modulus of the dry subgrade was 100 MPa. Climate zone 1 with six sub-seasons was chosen. Determining the remaining life showed that a 12% decrease in the dynamic modulus corresponded to a reduction in fatigue life of 15–25% depending on the structure. Further, an increase of measured strain with 18% corresponded to a reduction of the fatigue life with 48%.

5 Future work

Further studies need to be carried out in order to include the effects of climatic influence on the estimation of the lifetime of asphalt pavements. Testing different types of mixes with various mix compositions, such as mixes with higher and lower permeability characteristics, would be valuable in evaluating mixes that could be useful in pavement design, specifically with respect to deterioration caused by moisture impact. Testing asphalt mixture sensitivity to moisture should include the effects from short-term moisture damage (pore pressure conditioning) and long-term moisture damage, referring to moisture diffusion through the mastic, changing the rheological properties and weakening of the asphalt binder.

It has been mentioned in Section 4 that the tensile strain of asphalt pavement is traditionally estimated using the back-calculated modulus from FWD measurements. The work so far was based on a comparison between existing relationships for estimating tensile strain at the bottom of the asphalt layer and the measured strain. Thus, one idea for further research would be to compare the tensile strain of asphalt pavement estimated using a back-calculated modulus from FWD measurements with measured strain and estimated strain using the established relationship in this work.

Seasonal FWD measurements of existing roads would be valuable for the validation of the proposed relationship. Even the validation of the formula with a wider spectrum of input data would be valuable. Further study with a wider range of AC layer thicknesses, temperatures and moisture content for a better understanding of their impact on the tensile strain at the bottom of the AC layer is also recommended. In addition, it would be valuable to study the effect of temperature and moisture based on actual field conditions in which the new relationship can be validated.

The temperature effect on pavement is accommodated in pavement design programmes and in mixture design to a large extent. On the other hand, current pavement design methodologies make little use of precipitation data. Rather than just using static climate data, sensitivity analyses of the influence of climate change on the long-term performance of pavements would be beneficial. Durability models for flexible pavements must be developed to predict the service life based on functional properties and local climatic conditions. Ideally, the influence of climate should be implemented in pavement design models based on available data from meteorological stations, pavement material characterisations and currently used pavement design models. The value of these models lies in the available data of local climate conditions, such as temperature and moisture. To minimise the costs, road owners/operators must be able to adapt the design rules and specifications by using whole-life cost models, in which climatic impacts are taken into consideration to a greater extent.

6 Conclusions and recommendations

The results of this thesis highlight the importance of incorporating temperature and moisture impacts in assessing and designing pavements. The conclusions of the thesis are as follows:

1. Temperature and moisture content have shown significant (p <0.05) contributions to explaining the strain at the bottom of the AC layer.
2. Binder content, air void content and pore pressure conditioning have a significant (p <0.05) influence on dynamic modulus (|E*|) reduction.
3. Cyclic pore pressure conditioning results in decreases in dynamic moduli (12%) and increases in phase angles (8%), indicating weakening of the AC.
4. A relationship was developed between air void content and binder content under the influence of pore pressure cycles and the reduction of |E*|. The relationship was verified with a limited number of measurements on cores from a field study.
5. An enhanced relationship was developed between temperature, moisture content, surface deflection measurements and the tensile strain at the bottom of the asphalt layer. The relationship can be useful in the evaluation of the influence of environmental parameters at the strain level at the bottom of the AC layer.
6. Testing different types of mixes with various mix compositions, such as mixes with higher and lower permeability characteristics, would be valuable in the evaluation of mixes that could be useful in pavement design, specifically with respect to deterioration caused by moisture impact.
7. The development of a methodology for the practical determination of moisture content in pavement and for the estimation of moisture-related regional profiles would be valuable in pavement design.
8. Validation of the formula for estimating the tensile strain at the bottom of the asphalt layer with a wider spectrum in field conditions would be valuable.
9. The gained knowledge from this thesis can be used to develop guidelines for designing asphalt mixes with respect to climate impact, predicting the service life of asphalt pavement based on functional properties under the influence of various climate conditions, and reducing maintenance costs for highway agencies by minimising the risk of prematurely deteriorated pavements.

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