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Moisture Influence on Structural Behaviour of Pavements

Field and Laboratory Investigations

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Doctoral Thesis

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Abstract

The structural behaviour of pavements in cold regions can considerably be affected by seasonal variation in environmental factors such as temperature and moisture content. Along with the destructive effect of heavy traffic loads, climatic and environmental factors can considerably contribute to pavement deterioration. These factors can influence the structural and functional capacity of the pavement structures which, as a result, can trigger and accelerate pavement deterioration mechanisms. Studies on the influence of variation of the environmental factors on the response and behaviour of pavement materials have shown that proper consideration to these factors must be given in realistic pavement design and analysis.

In flexible pavement structures, particularly with a thin hot mix asphalt (HMA) layer, unbound materials and subgrade soil largely contribute to the overall structural behaviour of the pavement system. In unbound materials, moisture content and its variation can significantly affect pavement layer stiffness and permanent deformation characteristics. Therefore, the moisture condition of pavements and its influence on the mechanical behaviour of pavement materials has been of interest among the pavement research community. A proper understanding of moisture transformation in pavement systems and its effects on pavement performance are important for mechanistic pavement design.

The present summary of this doctoral thesis is based on four main parts. The first part of the thesis covers field measurements and findings from a test section along county road 126 in southern Sweden and consists of two journal papers (paper I and II) tackling different aspects of the research topic. This test section is located in a relatively wet ground condition and consists of a thin flexible pavement structure with a deep drainage system. It is instrumented with subsurface temperature, volumetric moisture content and groundwater probes. The mechanical response of the pavement structure was investigated using Falling Weight Deflectometer (FWD) measurements. The second part of the thesis (paper III and IV) are based on laboratory experiments and investigates different recent approaches that have been proposed to apply principles of unsaturated soil mechanics for incorporating seasonal variation of moisture content into the resilient modulus models using matric suction. The third part of the thesis (paper V) builds a bridge that spans between the laboratory and field investigations with an attempt to evaluate one of the predictive models presented in Paper III. The fourth part of the thesis (paper VI) mainly focuses on the laboratory-based investigation of the permanent deformation characteristic of subgrade soils. In this part, the permanent deformation characteristics of two different silty sand subgrade soils were investigated and modelled using the data obtained from repeated load traxial tests.

Paper I mainly focuses on the spring-thaw weakening of the pavement structure. The environmental data collected using different sensors and the FWD tests were used to investigate variations in moisture content with thaw penetration and its influence on the stiffness of unbound layers and the pavement's overall bearing capacity. Using the backcalculated layer stiffness and corresponding in situ moisture measurements in the unbound layers, a degree of saturation-based moisture-stiffness model was developed for the granular material and the subgrade.

In Paper II, the drainage system of the structure was manually clogged during a three month period in summer to raise the groundwater level and increase the moisture content of the layers. Along with the subsurface groundwater level and moisture content monitoring, the structural response of the pavement was studied. In this research work, the FWD tests were conducted at three different load levels. The stress dependent behaviour of the unbound granular layer and the subgrade soil were further studied using the multilevel loads FWD test data. Additionally, parameters of a nonlinear stress-dependent stiffness model were backcalculated and their sensitivity to in situ moisture content was studied.

In Paper III and IV, series of suction-controlled repeated load triaxial (RLT) tests were conducted on two silty sand (SM) subgrade materials. Several resilient modulus prediction models that account for seasonal moisture content variation through matric suction were summarized and after optimizing the model parameters, the capability of the prediction models in capturing the material response were evaluated.

In Paper V, an attempt was made to evaluate the proficiency of one of the suction-resilient modulus models using the field moisture content and FWD measurements from the Torpsbruk test site. The backcalculated subgrade stiffness dataset at different moisture contents were compared with resilient modulus models obtained from the suction-resilient modulus predictive model.

Paper VI presents an evaluation of several permanent deformation models for unbound pavement materials that incorporate the time-hardening concept using a series of multistage repeated load triaxial (RLT) tests conducted on silty sand subgrade materials. The permanent deformation tests were conducted at four different moisture contents with pore suctions measurement throughout the test. The effect of moisture content (matric suction) on the permanent deformation characteristics of the materials and the predictive model parameters were further investigated.

Keywords: Falling Weight Deflectometer (FWD), backcalculation, unbound material, subgrade, seasonal variation, moisture content, spring-thaw, drainage, pavement stiffness, field test, pavement instrumentation, resilient modulus, permanent deformation, repeated load triaxial test, unsaturated soil, matric suction.

Preface

The work presented in this doctoral thesis aims at providing more insight into the influence of moisture on the structural behaviour of pavements through field and laboratory investigations. This project was carried out at the Swedish National Road and Transport Research Institute (VTI), Department of Infrastructure Maintenance in collaboration with the Royal Institute of Technology (KTH), Department of Transport Science at the School of Architecture and the Built Environment (ABE). The laboratory experiments were carried out at the UNSAT Geotechnical Engineering Laboratory at the Arizona State University (ASU).

The Swedish Transport Administration (Trafikverket) is greatly appreciated for financing this research. The financial support of the Fredrik Bachman's Memorial Foundation (Stiftelsen Fredrik Bachmans Minnesfond) is also acknowledged.

I would like to express my sincerest gratitude to my supervisor, Prof. Sigurdur Erlingsson, for his generous support, encouragement and excellent guidance throughout the project. I am sincerely grateful to Assoc. Prof. Claudia Zapata at ASU for her great input and for providing me the opportunity to use the facilities at ASU. I would also like to thank Johan Ullberg, the contact person of this project at the Swedish Transport Administration, for his support throughout the project.

Many thanks to my colleagues at the Pavement Technology Division at VTI for creating a great work environment and fellow postgraduate students for their company, assistance and constructive contributions. Finally, I would like to thank my family and friends for their support and encouragement.

Farhad Salour

Linköping, March 2015

List of Symbols

ε_m	dielectric constant
c_0	light velocity in vacuum
l	length of metal rod in TDR probe
t	travel time in TDR probe
M_r	resilient modulus
σ_d	deviator stress
ε_r	resilient strain
ε_p	permanent strain
k_i	resilient modulus models material parameter
p_a	atmospheric pressure, 100 kPa
θ	sum of the principal stresses (bulk stress)
$\sigma_1, \sigma_2, \sigma_3$	principal stresses
τ_{oct}	octahedral shear stress
$M_{r_{opt}}$	resilient modulus at optimum moisture content
a	minimum value of the ratio $M_r / M_{r_{opt}}$
b	maximum value of the ratio $M_r / M_{r_{opt}}$
k_s	regression parameter
S	degree of saturation (S_r)
S_{opt}	degree of saturation at optimum moisture content ($S_{r_{opt}}$)
u_a	pore-air pressure
u_w	pore-water pressure
ψ_m	matric suction (ψ)
d_i	surface deflection measured at i mm distance from the centre of loading plate in FWD test
E_T	stiffness of HMA at temperature T
$E_{T_{ref}}$	stiffness of HMA at temperature $T_{ref} = 10°$ C
b	constant for the HMA stiffness model
T	temperature of HMA layer
T_{ref}	reference temperature for HMA layer $T_{ref} = 10\,°\mathrm{C}$
Δu_{w-sat}	pore-water pressure build-up under saturated condition
ψ_{m_0}	initial matric suction
$\Delta \psi_m$	relative change in matric suction
$w(\psi)$	volumetric water content at matric suction ψ
$C(\psi)$	correction factor for Fredlund and Xing SWCC model
ψ_r	soil matric suction at residual condition

a_f	model parameter for Fredlund and Xing SWCC model
n_f	model parameter for Fredlund and Xing SWCC model
m_f	model parameter for Fredlund and Xing SWCC model
p_0	reference pressure, 100 kPa
R^2	coefficient of determination
R^2_{adj}	adjusted coefficient of determination
w	gravimetric water content (W_c)
w_{opt}	optimum gravimetric water content
p	hydrostatic stress
$\hat{\varepsilon}_p{}^{3000}$	accumulated permanent strain at 3000th load cycles in the RLT test
$\hat{\varepsilon}_p{}^{5000}$	accumulated permanent strain at 5000th load cycles in the RLT test
$\hat{\varepsilon}_p$	accumulated permanent strain
N	number of load applications
q	cyclic deviator stress
ε_0	material parameter of the Tseng and Lytton model
ρ	material parameter of the Tseng and Lytton model
β	material parameter of the Tseng and Lytton model
ε^0	material parameter of the Gidel et al. model
B	material parameter of the Gidel et al. model
u	material parameter of the Gidel et al. model
$L_{\max}$	a parameter of the Gidel et al. model expressed as $L_{\max} = \sqrt{p_{\max}^2 + q_{\max}^2}$
$p_{\max}$	maximum applied hydrostatic stress
q_f	deviator stress at failure
m	slope of the Mohr-Coulomb failure line in $p-q$ space
s	intercept of the Mohr-Coulomb failure line in $p-q$ space
C	material parameter of the Korkiala-Tanttu model
c	material parameter for determination of the b parameter for the Korkiala-Tanttu model
d	material parameter for determination of the b parameter for the Korkiala-Tanttu model
b	material parameter of the Korkiala-Tanttu model
R	ratio of the applied deviator stress to the deviator stress at failure, determined using static triaxial tests
A	parameter of the Korkiala-Tanttu model usually taken as 1.05

i	stress path number
N_i	total number of load applications at the end of the i^{th} stress path
N_i^{eq}	equivalent number of load applications
$\hat{\varepsilon}_p(N)$	accumulated permanent strain after N number of load applications
$\hat{\varepsilon}_{pi}$	accumulated permanent strain at the end of the i^{th} stress path
Δq	cyclic deviator stress
$\gamma_{d_{\max}}$	maximum dry unit weight

List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
APT	Accelerated Pavement Test
BCI	Base Curvature Index
BDI	Base Damage Index
CCP	Constant Confinement Pressure
FE	Finite Element
FWD	Falling Weight Deflectometer
GPR	Ground Penetrating Radar
GW	Groundwater
HAE	High Air-Entry
HMA	Hot Mix Asphalt
HVS	Heavy Vehicle Simulator
LTPP	Long-Term Pavement Performance
LVDT	Linear Variable Differential Transformer
MC	Moisture Content
MEPDG	Mechanistic Empirical Pavement Design Guide
PI	Plasticity Index
PVC	Pressure-Volume Controller
RLT	Repeated Load Triaxial
RMSD	Root-Mean-Square Deviation
SCI	Surface Curvature Index
SG	Specific Gravity
SPA	Seismic Pavement Analyser
SSE	Sum of Squared Errors
SSI	Structural Strength Index
SWCC	Soil-Water Characteristic Curve
TDR	Time Domain Reflectometry
USCS	Unified Soil Classification System
VCP	Variable Confinement Pressure

List of Publications

Paper I	Salour F. and Erlingsson S. (2013). Investigation of a Pavement Structural behaviour during spring-thaw using falling weight deflectometer. *Road Materials and Pavement Design*, Vol. 14, No. 1, pp. 141-158, DOI: 10.1080/14680629.2012.754600. *The author of this thesis carried out the analysis of the data and the write-up.*
Paper II	Salour F. and Erlingsson S. (2013). Moisture Sensitive and Stress Dependent Behaviour of Pavement Unbound Materials from In-Situ Falling Weight Deflectometer Tests. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2335, Transportation Research Board of the National Academies, pp. 121-129, DOI: 10.3141/2335-13. *The author of this thesis was involved in planning of the FWD tests, carried out the analysis of the data and the write-up.*
Paper III	Salour F., Erlingsson S. and Zapata, C. E. (2014). Modelling Resilient Modulus Seasonal Variation of Silty Sand Subgrade Soils with Matric Suction Control. *Canadian Geotechnical Journal*, Vol. 51, No. 12, pp. 1413-1422, DOI: 10.1139/cgj-2013-0484. *The author of this thesis carried out the suction-controlled repeated load triaxial tests, analysis of the data and the write-up.*
Paper IV	Salour F. and Erlingsson S. (2015). Resilient Modulus Modelling of Unsaturated Subgrade Soils: Laboratory Investigation of Silty Sand Subgrade. *Road Materials and Pavement Design* (in Press), DOI: 10.1080/14680629.2015.1021107. *The author of this thesis carried out the suction-controlled repeated load triaxial tests, analysis of the data and the write-up.*
Paper V	Salour F., Erlingsson S. and Zapata, C. E. (2015). Evaluating a Model for Seasonal Variation of Silty Sand Subgrade Resilient Modulus with FWD Tests. The Transportation Research Board 94th Annual Meeting, January 2015, Washington, D.C. USA. (under publication for *Transportation Research Record: Journal of the Transportation Research Board*). *The author of this thesis was involved in planning of the FWD tests and carried out the suction-controlled repeated load triaxial tests, analysis of the field data and the write-up.*
Paper VI	Salour F. and Erlingsson S. (2015). Permanent Deformation Characteristics of Silty Sand Subgrades from Multistage RLT Tests. Submitted to *International Journal of Pavement Engineering.* *The author of this thesis carried out the suction-controlled repeated load triaxial tests, analysis of the data and the write-up.*

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1. Introduction

1.1. Background

The road network is an important element of the national infrastructure and its construction, operation, and maintenance constitute a large part of the national annual budget. Roads are built to provide road users a safe, comfortable and robust ride throughout their service life. They must basically fulfil the two major functional and structural requirements. The functional requirement or serviceability is to provide skid resistance and a smooth ride experience for the users, and structural requirement is to provide an adequate level of structural adequacy over a reasonable time period.

Pavement structures are primarily designed to distribute the traffic induced stresses and strains over the load bearing layers to an intensity level which the material can withstand. In mechanistic-empirical pavement design, inputs such as material properties, traffic loads and structural layer thicknesses are related to the pavement response such as stresses and strains, using mechanistic principles. The pavement response is then used to predict pavement performance using laboratory and field based data and measurements. Pavement design dependency on field and laboratory performance and observations is mainly due to the complex nature of pavement systems and the many system boundary conditions which affect its performance. These boundary conditions are mainly the interaction of climatic factors such as temperature and moisture (water) content, the mechanical behaviour of bound and unbound materials, and the traffic load spectrum and frequency. Due to the complexity of pavement systems, the theory alone has not yet been able to realistically predict pavement performance, and pavement engineering is still dealing with fundamental difficulties in many aspects of the design process.

To overcome the limitations of empirical pavement design, the pavement engineering research community have been moving towards a so-called mechanistic approach in which the pavement structure and environment are treated as a system and the pavement mechanical response is analysed, taking into account the external traffic loading and environmental conditions simultaneously. Even though great developments have been achieved with the enhancement of computers that allows for more advanced analysis and design procedures, the transition towards a fully mechanistic design with improved design reliability and distress prediction models still requires a better understanding of the factors and mechanisms involved. This will then allow for feasibly relating the limited laboratory and field based data to the design process. The mechanistic pavement design method will evidently be more flexible to accommodate various loads, materials and climatic conditions.

In thin flexible pavement structures, unbound layers such as granular base and subbase materials, as well as the subgrade material, play a significant role in the overall pavement performance. In order to establish a more robust and rational pavement design and analysis, a thorough understanding of the factors involved, such as material behaviour and response to traffic-load induced stresses and environmental factors, is essential.

Flexible pavement structures with a thin HMA layer (≤ 100 mm HMA layer thickness) and unsurfaced gravel roads constitute a large part of the road network in Sweden. Depending on the governmental policies and available funds, these secondary low volume roads may not receive a sufficient construction and maintenance budget. In addition to the traffic load distresses that can be considerable due to the heavy axle loads of the forest industry, these roads are often exposed to significant environmental effects. These pavement structures usually experience considerable temperature and moisture variations since they are exposed to rain, snow, frost and freeze-thaw cycles during a significant period of the year. The cold region-related climatic and environmental factors can expose pavements to intense loading that can result in seasonal and long term loss of bearing capacity (structural shortage), or loss of surface smoothness due to differential frost action, crack propagation and surface ravelling (serviceability shortage). Furthermore, these environmental factors, when accompanied with traffic loading, can accelerate the traffic-related deterioration mechanisms.

1.2. Objective and scope of the research

The aim of this study was to improve knowledge about the impact of moisture content and its seasonal variation on the structural response of pavement structures. More precisely, the in situ and laboratory response of pavement unbound layers and silty sand subgrade soils with respect to change in the moisture content were of interest. In the laboratory-based studies in particular, an attempt was made to take into account the unsaturated condition of the soil (i.e. incorporating soil suctions) in mechanical response modelling of the material. The specific objectives at different stages of the research project within the overall vision of the study were as follows:

- Monitoring short term and long term seasonal variations in groundwater level, pavement profile temperature and moisture content through field instrumentation.
- Investigating the influence of environmental factors on pavement layers mechanical response and overall stiffness based on field measurements.
- Examining the efficiency of the subsurface drainage system in removing the excess moisture from the pavement structure for possible improvement considerations.

- Analysing the moisture sensitivity and stress dependency of the granular base and subbase material and subgrade soil through backcalculation of the surface deflection data.
- Studying the feasibility of backcalculating material behaviour model parameters from multilevel loads FWD measurements.
- Understanding the effect of soil suction on the resilient behaviour of silty sand (SM) subgrade soils with high fines content.
- Investigating several laboratory based suction-resilient modulus predictive models and implementing the modified models for silty sand (SM) subgrade materials.
- Evaluating the laboratory based suction-resilient modulus models with field measurements and FWD data.
- Feasibility study of using multistage RLT tests for permanent deformation characterization and modelling of fine-grained subgrade materials.
- Investigating the effect of moisture content variation on the permanent deformation characteristics of silty sand subgrade soils.

To achieve the objectives of the study, both field and laboratory based studies have been carried out. In the following, a summary based on the six appended journal papers are presented.

2. Pavement Environmental Factors

Pavement structures and their surrounding environment are in continuous interaction. Similar to their surrounding environment, pavement structures can also be characterized by temperature, moisture content and acting pressure regimes which are governed by the physical laws of the pavement porous mineral system (Doré and Zubeck, 2008). These parameters undergo daily and seasonal variations as well as a spatial distribution as they are interconnected to the constantly evolving environment that surrounds the pavement system. The two main environmental factors in pavement engineering are temperature and moisture content.

2.1. Pavement temperature regime

Pavement temperature is mainly governed by the pavement system boundary conditions and the system's available energy. The temperature of the materials of the pavement layers and its variation highly depends on the surrounding environmental conditions, the location within the pavement system and the thermodynamic properties of each material. While the temperature at the lower depths in the pavement system is almost constant throughout the year, being nearly equal to the mean annual atmospheric temperature, the temperature in the top part of the system usually shows considerable daily and seasonal variations due to a more direct pavement-atmosphere interaction as well as exposure to surface solar radiation (Dysli et al., 1997; Hermansson, 2004; Doré and Zubeck, 2008). The pavement temperature regime therefore varies between a nearly stable bottom temperature and a constantly fluctuating surface temperature (pavement thermal regime trumpet). Figure 1 shows a 2 m deep temperature profile in a pavement structure in southern Sweden during a three month period.

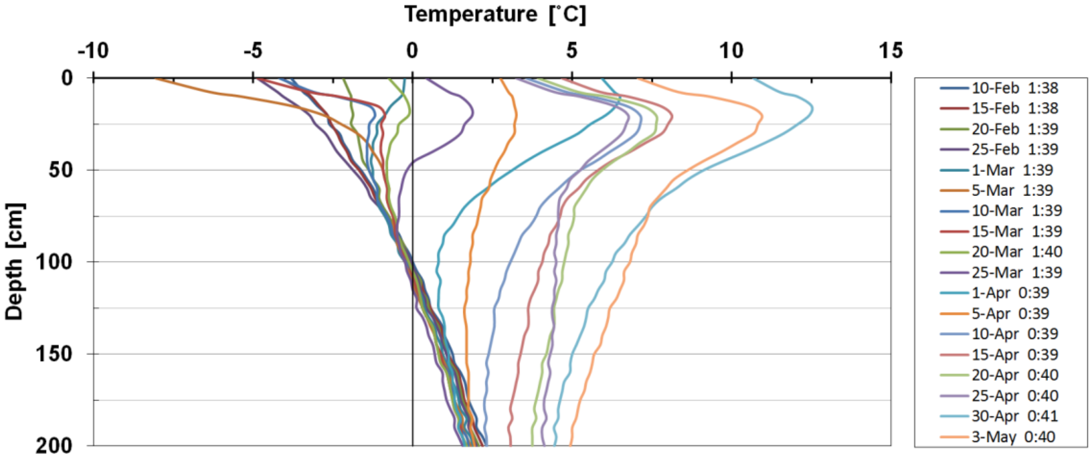

Figure 1. Trumpet pavement temperature profile and its variation from February to May, 2010. Measurements are from the test site along county road 126 in southern Sweden. (Geographical coordinates: +57 3' 1.66", +14 34' 8.26")

There are two main factors that contribute to pavement heat intake: solar radiation of the asphalt concrete surface layer and geothermal heat flux; and two factors that contribute to heat extraction: surface convection and radiation emissions (Hermansson, 2000; Doré and Zubeck, 2008). Heat may also be induced into or extracted from the pavement system due to condensation/evaporation, latent heat of fusion if pavement material pores contain moisture or ice lenses and heat exchange due to precipitation.

Pavement temperature monitoring

In many countries in the northern hemisphere where pavements experience considerable seasonal frost conditions, load restrictions are commonly imposed during the spring-thaw period to prevent severe pavement deterioration. During this period, the pavement structures are usually exposed to excess moisture content which results in reduced bearing capacity in unbound layers and therefore high resilient and permanent deformations. Monitoring a pavement's environmental conditions such as frost zone (temperature) and moisture content can help road authorities to decide where and when to apply and enforce or to remove load restriction.

In Sweden, monitoring pavement temperature profiles is carried out. The pavement temperature monitoring program consists of continuous pavement temperature measurements from sites that are spread over the country's road network using the Tjäl2004 equipment. The Tjäl2004 is a frost rod that was developed at the Swedish National Road and Transport Research Institute, VTI (Wilhelmson et al., 2004). It consists of a series of temperature sensors mounted along a metal rod which are placed in a casing. The temperature sensors are located at 50 mm intervals throughout the pavement profile and down to a depth of 2 m. These temperature sensors register data at determined time intervals (usually every 30 minutes) using a data logger that is supplied with a battery. The temperature sensors are calibrated at 0° C to have the highest accuracy in detecting the frost zone. The data are then distributed online via the internet (http://www3.vv.se/tjaldjup). This database assists the local road authorities to give permission or forbid heavy axle load passages during certain periods by controlling the frost zone condition in the pavement structure. Figure 2 shows typical registrations from November 2010 to April 2011 from the station along county road 126 near Torpsbruk in southern Sweden. The overall formation of the frost zone, repeated frost-thaw cycles in the upper part of the pavement, and the thaw penetration can be seen in Figure 2.

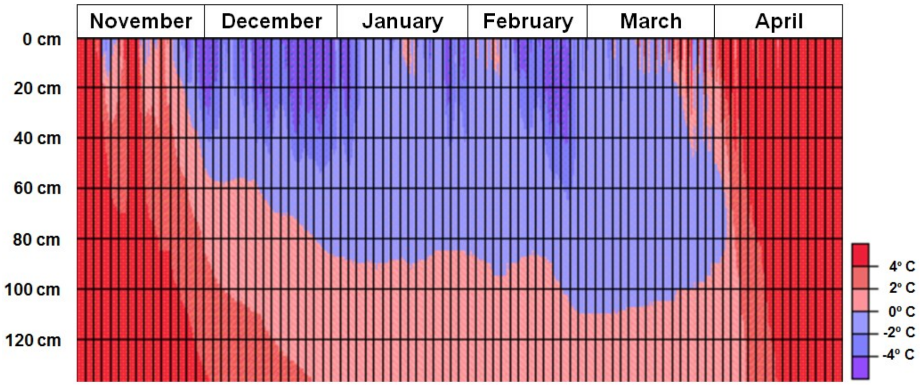

Figure 2 Typical Tjäl2004 frost rod measurements from county road 126 near Torpsbruk in southern Sweden (November 2010 to April 2011).

In Finland the Percostation system is used to optimize the use of load restrictions throughout the road network (Vuorimies, 2004). Percostation consists of electrical conductivity, dielectric value, and temperature sensors that are collected using eight individual channels with minimum measurement intervals of 60 seconds. The measured data are then stored in a data collection unit which can be read using a modem connection. The collected data are further analysed and the condition of different pavement layers and subgrade is assessed. The data are then compared to the critical limits and the decisions to impose or lift load restrictions and to determine the maximum allowed axle load and/or number of axles are made.

2.2. Pavement moisture regime

Moisture condition in pavement structures continuously evolves throughout the year (Erlingsson et al., 2002; Doré and Zubeck, 2008; Erlingsson et al., 2009a). The moisture content of the unbound material that is usually set close to the optimum during the compaction in the construction phase will eventually change towards a natural equilibrium state (Zapata et al., 2009). Similar to the temperature condition of the pavement, the moisture regime is also governed by the boundary conditions of the system. The natural equilibrium moisture content is greatly dependent on the material properties and distance to the groundwater table level and its variation. Generally, the moisture condition at the bottom of the pavement system is relatively stable. However, at the upper sections in pavement systems, moisture condition can vary widely from very dry conditions to fully saturated states due to climatic events. The moisture condition of the upper section of the pavement greatly depends on the surface characteristics as well as its longitudinal and transverse position within the pavement system (Doré and Zubeck, 2008). The moisture content of the materials close to the pavement edges and in the vicinity of surface cracks usually shows higher variations due to climatic events such as rainfall (Hansson et al., 2005).

The moisture evolution of the pavement systems throughout the year is the result of a complicated interaction of several factors that contribute to moisture intake and removal from pavement systems. There are four sources that contribute to moisture intake in pavement structures: infiltration of precipitation water, lateral moisture transfer, capillary rise and frost-thaw action. The two main factors that contribute to moisture extraction from pavement systems are moisture drainage and moisture evaporation (Doré and Zubeck, 2008; Erlingsson et al., 2009b). Figure 3 illustrates the factors that contribute to moisture regime variations in pavement structures.

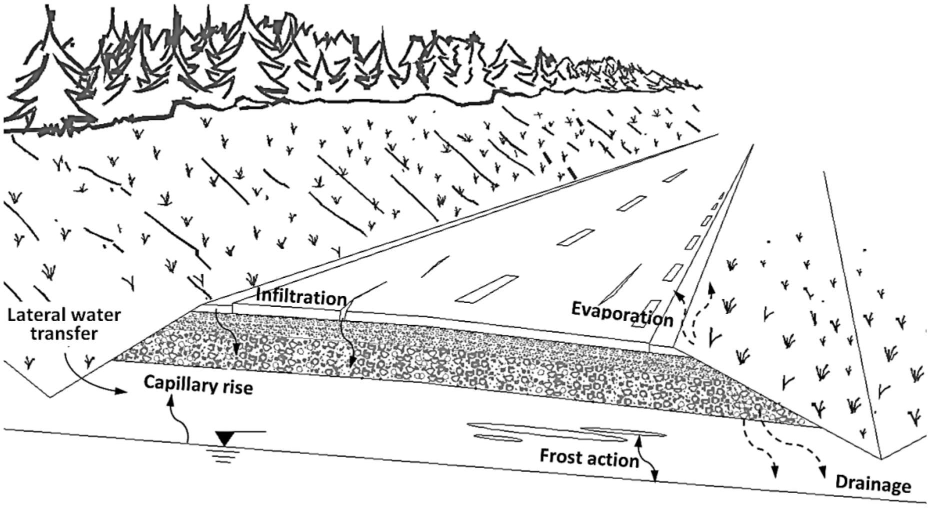

Figure 3. Factors contributing to the moisture regime and its variation in pavement systems.

With respect to the moisture content, the pavement structure profile can be divided into several sections. Assuming that groundwater table exist at a certain depth below the structure, the pavement profile can be divided into two distinct zones. Above the groundwater table is the vadose zone in which the unbound materials are in unsaturated state. Below the groundwater table is the saturated zone in which all the pores are completely filled with water. The moisture content profile within the vadose zone varies from the saturated state at its base to the natural material moisture state at the upper extent and can be divided into three sub-zones: the capillary zone, the intermediate vadose zone and the surface water zone (Erlingsson et al., 2009b). In the capillary zone or the capillary fringe, the water from the groundwater table is pulled upwards due to the capillary forces. Water is almost filling all of the voids and the air phase is discontinuous and therefore the pore-water pressure is less than the atmospheric pressure. Depending on the grain size distribution and the material properties, the thickness of the capillary zone can vary from few centimetres up to few metres. In the intermediate vadose zone, the remaining of the drained water is held, also due to the capillary forces. In this zone both the air and the water phases are continuous. In the surface water zone, air is filling most of the voids and the water phase is discontinuous mainly holding in form of water packs. The water content of the intermediate vadose zone and the surface zone can considerably vary throughout the year as water may infiltrate into the pavement structure during wet raining seasons and spring-thaw periods (Erlingsson et al., 2009b). A conceptual schematic of different regions of water in a pavement structure is shown in Figure 4.

Variation in the moisture content in pavement layers, can affect the mechanical properties of the material through different mechanisms. In coarse-grained materials, increase in moisture content can reduce the inter-particle friction and contact forces due to water lubrication effects between the contact area of the particles. In unbound materials with high fines content (e.g. subgrade soils), moisture variation can additionally affect the state of stress of the material through pore suction and pore pressure effects.

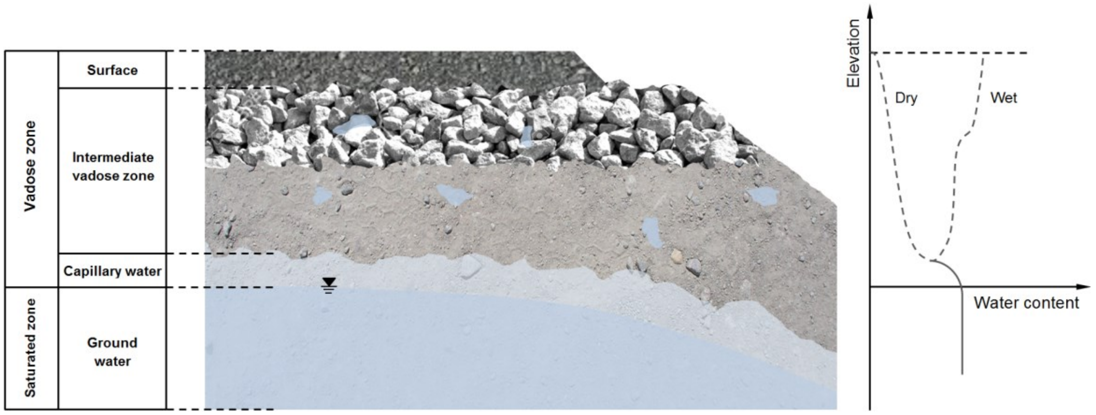

Figure 4. Conceptual schematic of the regions of surface water in pavement structures.

Pavement moisture monitoring

It is well known in pavement engineering that moisture can have a significant detrimental effect on the performance and bearing capacity of pavement structures. Excess moisture presence in pavement structures usually results in accelerated pavement distresses, particularly when combined with heavy axle loads. Both field observations and laboratory based research studies have shown that proper drainage can greatly improve pavement performance and increase its service life. Then, understanding moisture variation and movement in pavement structures and moisture-related distresses have become of great interest among the pavement research community. This has resulted in development of non-destructive techniques for in situ real-time measurement of moisture content within the pavement systems. The commonly used methods for moisture measurements in pavement engineering applications are Time Domain Reflectometry (TDR) technique, capacitance measurement and Ground Penetrating Radar (GPR).

Time Domain Reflectometry

Time Domain Reflectometry (TDR) is a very practical technique for measuring the in situ moisture content of unbound materials and subgrade soils. TDR technique applies electromagnetic technology to measure the relative dielectric constant or relative permittivity of a medium. In a multi-phase medium, the overall dielectric number ε_m is highly dependent on the dielectric numbers of the constituents. The volume fraction of the constituents is governing the overall dielectric number. In unbound granular material and subgrade soils the multi phases mainly consist of solid constituents, water and air. The relative dielectric number of soil constituents and air is much smaller than that of water $\varepsilon_{soil} \approx 2-8$, $\varepsilon_{air} \approx 1$ and $\varepsilon_{water} \approx 77-88$. Therefore, the volumetric moisture content of the soil can be determined by measuring its overall dielectric number (Topp and Davis, 1985; Erlingsson et al., 2009a; Fredlund et al., 2012).

In the TDR technique, a very short electric pulse is sent through a waveguide which consists of 2 or 3 metallic rods. The impedance discontinuity at the end of the waveguide results in backward reflection of the electric pulse which is then detected by a receiver. By measuring the travel time of the electric pulse and knowing the length of the waveguide, the propagation velocity of the electromagnetic wave can be measured. The dielectric constant of the soil medium is thereafter determined as follows:

$$\varepsilon_m = (\frac{c_0 t}{2l})^2 \qquad [1]$$

where ε_m is the dielectric constant, ε_0 is the light velocity in vacuum and t is the travel time of the electromagnetic pulse and l is the length of the metallic rods. TDR probe readings are usually reported as the volumetric moisture content through an empirical regression which is derived from analyses based on a variety of soil types (Topp et al., 1980; Hu et al., 2010). However, the moisture content can also be reported as the gravietric mositure content or degree of saturation using volume-mass relations. Figure 5 shows installation of TDR probes in a thin flexible test road section in Iceland (Erlingsson et al., 2002).

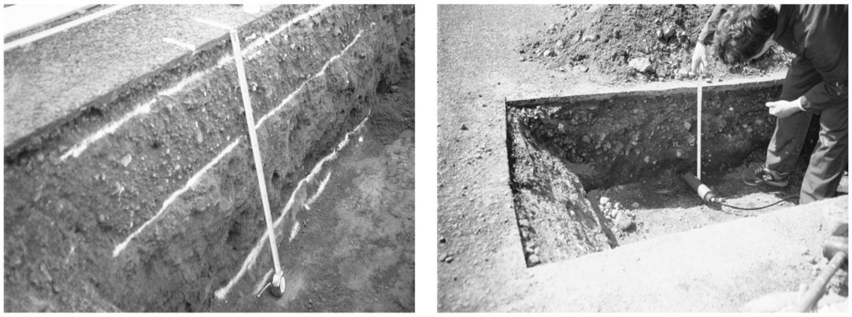

Figure 5. Pavement layer thicknesses and installation of TDR probes (Erlingsson et al., 2002).

Capacitance measurement

Capacitive sensors can also be used to measure the moisture content of the pavement layers (Dirksen, 1999; Hu et al., 2010; Fredlund et al., 2012). Commonly used capacitance sensors consist of two electrodes separated by a dielectric. An oscillator applies a high frequency electromagnetic pulse (50 to 150 MHz) to the electrodes which in return provides a resonant frequency. A capacitance field is generated between the two electrodes of each sensor which is extended into the soil next to the sensors. An array of sensors in the access tube which is inserted in the pavement structure logs the output frequency. The capacitance technique measures the apparent dielectric constant of the soil medium which is further empirically related to the soil moisture content through a non-linear calibration. The greater the soil moisture content, the smaller the resonance frequency and the apparent dielectric constant (Topp et al., 1980; Fares and Polyakov, 2006). The soil relative dielectric constant is related to the unfrozen moisture content and frozen moisture has only a minor influence on the dielectric constant (Patterson and Smith, 1981). Once a proper calibration is done, the capacitance technique can measure the apparent liquid moisture content of the soil with high accuracy. Figure 6 shows a capacitance probe and installation of a moisture rod in a test site in southern Sweden. Figure 7 represents one-year volumetric moisture content measurements at four different depths in a pavement structure (depth 50 cm is in the subbase layer and depths 90, 120 and 150 cm are in subgrade).

Figure 6. Capacitance moisture probe (left) and installation of a moisture rod in a test site in southern Sweden (photos from Klas Hansson).

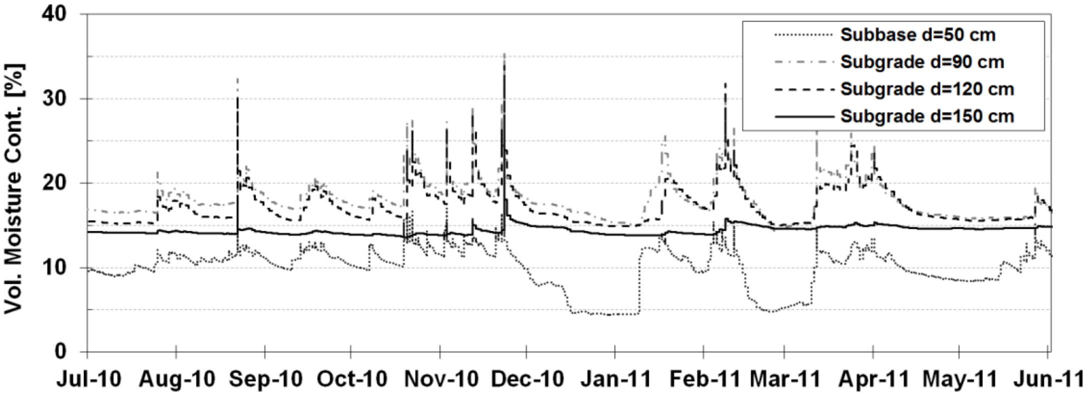

Figure 7. Volumetric moisture content measurements at Torpsbruk test site along county road 126 in southern Sweden.

Ground Penetrating Radar

Ground Penetrating Radar (GPR) is a non-destructive testing technique that is used to determine material thickness, frost depth, and groundwater table level as well as the moisture content (Saarenketo and Scullion, 2000). This technique is usually used for larger investigations such as monitoring the pavement system conditions at network level. A GPR device is basically a radar system that uses a transmitter to send electromagnetic waves. The electromagnetic wave penetrates the pavement structure and the reflected wave is detected by a receiver. Based on the travel time and the strength of the reflections, the dielectric constant of the material layers and therefore their moisture content can be determined.

2.3. Pavement behaviour in cold regions

In cold regions, frost action is one of the main sources of excess moisture presence in pavement structures. Frost penetration in unbound materials and subgrade soils can result in frost heave in the pavement structure and accumulation of water in the pavement structure in the form of ice lenses which in turn cause weakening during the spring-thaw (Hermansson and Guthrie, 2005). There are two conditions required for frost action to occur in a pavement structure: a sufficiently low temperature for sufficient length of time that can result in a phase change of pore water and the presence of moisture and free transfer of the moisture to the freezing front (Coussy, 2005; Doré and Zubeck, 2008; Hermansson et al., 2009).

All the general sources of moisture presence in pavement structures, mentioned earlier, can contribute to supplying frost action in pavements. These two conditions of temperature and moisture presence are generally fulfilled in pavements in cold regions. However, the severity and extent of the frost action can vary depending on the geographical position and the climate of the region.

Frost action mechanism

Frost progression in the pavement structure disrupts the thermodynamic equilibrium of the pavement system, thus introducing a thermal gradient. This leads to a series of complex processes that includes the coupled effects of thermal and chemical potential at soil particle-water-ice interfaces that act alongside the soil particle mechanical contact forces (Henry, 2000; Doré and Zubeck, 2008). When frost penetrates the pavement structure, the interstitial moisture in the soil mass begins to convert into ice crystals, thus reducing the unfrozen moisture content in the pores. The latent heat of the pore water crystallization causes the temperature to slightly increase near the freezing point before it begins to decrease again, which results in the freezing of most of the remaining free interstitial moisture. At this point, only the hygroscopic moisture (the water held tightly on the surface of soil colloidal particle) remains unfrozen. This complex procedure in the pavement system creates three distinct zones along the pavement profile: the bottom part of the pavement profile remains at temperatures above the freezing point and in a completely unfrozen moisture phase; the transitional zone (with partly frozen interstitial water) in which the free moisture and the ice crystals coexist with a proportion profile that is governed by the temperature profile; and finally, the upper part of the pavement profile, where all the water except for the hygroscopic moisture is in a completely frozen state (Doré and Zubeck, 2008; Hermansson et al., 2009). The intermediate zone, which can be up to several decimetres thick, plays a significant role in attracting excess moisture into the pavement structure. The moisture attraction mechanism is described in the following paragraphs.

Formation of ice crystals in soil mass pores exerts pressure on the remaining unfrozen moisture. Since ice crystals occupy more space than the liquid moisture, they create smaller radii soil particle-water-ice interfaces. The contractile skin which is the water film that is in contact with the ice crystals works as a membrane in tension that resists the ice crystal pressures. This generates a negative pressure in the interstitial moisture which results in higher suction in the soil mass. The suction gradient between the top and the bottom of the intermediate zone creates a condition in which moisture flows upward towards eventual ice lenses along this zone. The upward flow of the moisture in the intermediate zone occurs as long as the partly frozen zone remains permeable. The permeability of the intermediate zone usually varies from unfrozen soil permeability at the bottom of the pavement profile to the eventually impermeable zone at the top of the pavement where pores are filled with water crystals with no free moisture paths. Since the free moisture passage is not fulfilled in the system due to the impermeability of the soil at the top of the pavement, and eventually the negative pressure gradient exceeds the overburden pressure, soil particles separate and ice lenses grow so that the moisture from the underlying intermediate zone can be extracted. The moisture mitigation to the growing ice lenses continues at the frozen fringe, resulting in expansion of the ice lenses.

At the beginning of the process, the ice lenses form at shallow depths in a frozen fringe with a sharp temperature gradient. Therefore, heat is extracted rapidly, the system cools and the hydraulic conductivity at the frozen fringe is rapidly reduced. The freezing front develops downward and another ice lens forms at a location where the negative pressure and the overburden pressure become equal. Both the thermal gradient and the cooling rate of the frozen fringe are reduced with depth, which results in slower and longer ice lens growth and therefore thicker and more widely-spaced ice lenses. This procedure continues as far as the heat is effectively extracted from the frozen fringe (Doré and Zubeck, 2008). The mechanism of formation of ice lenses in freezing pavement structures is illustrated in Figure 8.

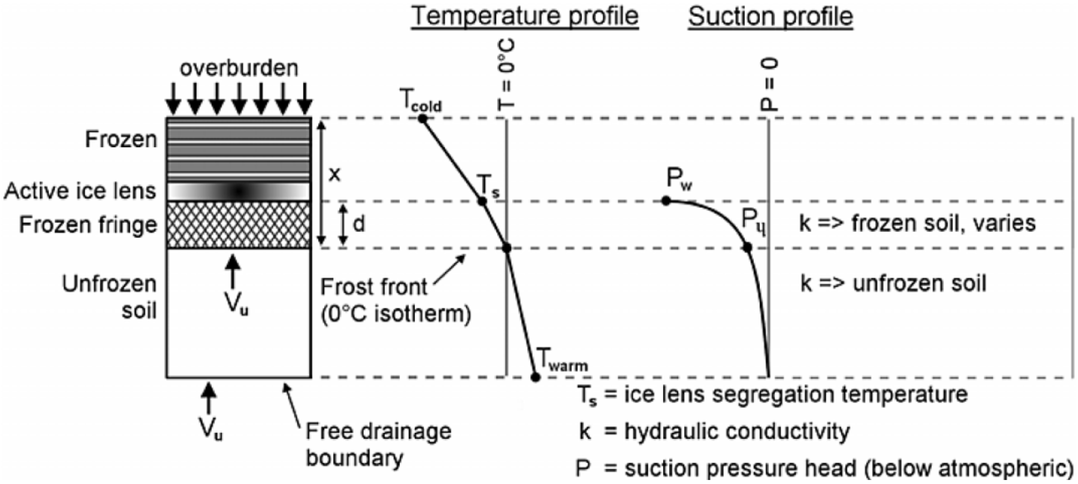

Figure 8. Temperature and suction gradient along pavement profile during the formation of an ice lens. (modified after Mokwa, 2004).

The frost penetration process is a relatively long procedure that results in continuous accumulation of moisture content in the pavement system in the form of ice lenses. In addition to the frost heave related problems that might occur if frost susceptible materials are present in the pavement structure, the thawing of the frost zone becomes a major consequent problem. The large quantity of moisture that is accumulated in the pavement system during the freezing period is released over a much shorter period as the thaw penetrates the pavement in the spring and the ice lenses convert back to liquid moisture. This usually leads to loss of bearing capacity of the pavement structure during the spring-thaw period.

3. Emergence of Unsaturated Soil Mechanics in Pavement Engineering

As discussed in the previous chapter, the unbound layers in pavement structures and the upper part of the subgrade can experience considerable variation in the moisture content throughout the year. The moisture content of the unbound layers can fluctuate seasonally from the natural equilibrium condition due to several reasons, i.e. winter frost action and spring-thaw in cold regions, infiltration during rain events and variation in the groundwater table.

Even though the underlying materials in pavement structures are generally in partially saturated conditions, the impact of an unsaturated state on the mechanical behaviour of the unbound materials and subgrade soils is generally not taken into account. The performance of the pavement structures can to a large extent be affected by the behaviour of the underlying unbound materials and more reliable performance prediction of pavement systems require consideration for the unsaturated state.

The mechanical behaviour of the soil is generally governed by the stress variables that control the equilibrium of the soil structure (Fredlund and Morgenstern, 1977). An unsaturated soil element consists of four different phases: soil particles or solid phase, water phase, air phase and the contractile skin. The total equilibrium equation of this four-phase soil structure can be formulated using the force equilibrium equation for the air phase, water phase, contractile skin phase and the total equilibrium equation for the soil element (Fredlund et al., 2012).

From the equilibrium equation of the unsaturated soil structure, three independent sets of normal stresses can be extracted to form the stress state variables. These three normal stress state variables are $(\sigma - u_a)$, $(u_a - u_w)$ and u_a, where σ is the total normal stress and u_a and u_w are pore-air and pore-water pressures, respectively. The difference between the pore-air and pore-water pressures $(u_a - u_w)$ within the unsaturated soil structure is known as the matric suction (ψ_m). Assuming that the soil particles are incompressible, the stress variable u_a can be eliminated and therefore the stress state variables for the unsaturated soil structure can be defined as $(\sigma - u_a)$ and $(u_a - u_w)$ (Fredlund et al., 2012). As the moisture content of the soil increases and the soil structure goes from an unsaturated state to a fully saturated state (S =100%) the pore-water pressure approaches the pore-air pressure and therefore the matric suction of the soil structure $(\psi_m = u_a - u_w)$ goes toward zero. Matric suction is therefore known to be the state variable with the highest relevance to unsaturated soil mechanics. The matric suction of the subgrade is highly dependent on the moisture content of the soil structure, commonly defined by the soil-water characteristic curves.

Since matric suction of the soil structure is directly related to its moisture content, and moisture is the main environmentally driven factor affecting the behaviour of unfrozen unbound layers, matric suction can be incorporated into the material response characterization models (i.e. the stiffness) for capturing the seasonal moisture variation effects. Accounting for suction effects in the mechanical behaviour of unbound materials is particularly important in materials with a high fines content (i.e. in subgrade soils) (Khogali et al, 1991; Zapata et al., 2009).

3.1. Soil matric suction measurement

Matric suction is the difference between the pore-air and pore-water pressures within the unsaturated soil structure. Matric suction measurement can be done through direct and indirect measurements. In the direct measurement method, only the negative pore-water pressure is measured as the pore-water pressure is usually equal to the atmospheric pressure. A Tensiometer is the most commonly used device for direct measurement of negative pore-water pressure in the field. It consists of a high-air-entry (HAE) porous ceramic cup that is attached to a pressure gauge with a small plastic tube, filled with de-aired water. Once the HAE ceramic cup is in contact with the soil particles and the equilibrium is reached, the water in the tube will have the same negative pressure as the soil pore-water pressure that can be read using the device pressure gauge. This measurement is numerically equal to the matric suction if the pore-air pressure is equal to the atmospheric pressure. The indirect measurement of the matric suction is done by measuring a different variable than the negative pore-water pressure.

In indirect measurement methods, the electrical or thermal conductivity of a porous material, which is a function of its moisture content, is measured. Since water content is also a function of the matric suction, the matric suction of the sensor and the surrounding soil can be determined using predefined calibration curves (Fredlund et al., 2012).

3.2. Axis translation technique

The negative pore-water pressure that can be directly measured with a tensiometer is limited to about -1 atm. (~-100 kPa) as there is the risk that the water in the tensiometer may begin to cavitate and interfere the measurements. In order to measure matric suctions over this range, the axis translation technique is usually employed in the laboratory. In this technique, the soil specimen is exposed to a certain air pressure in a closed chamber, and therefore the origin of the pore-water pressure is translated from the standard atmospheric pressure to the air pressure of the chamber. Thus, the risk of cavitation is avoided as the pore-water pressure does not go below -1 atm. In other words, both the pore-air and pore-water pressures are translated, while the matric suction $(u_a - u_w)$ in the specimen is maintained (Hilf, 1959; Fredlund, 1989).

3.3. Soil-water characteristic curve

The soil-water characteristic curve (SWCC) is one of the most important functions used in assessment of unsaturated soil properties. SWCCs combine the water content measurement (mass or volume) of the unsaturated soil structure to the energy state of the water phase (matric suction). In other words, the relationship between the soil moisture content and the matric suction is usually represented by the SWCC. The SWCC of the soil depends on the water distribution in pores as well as the soil texture and gradation (Fredlund et al., 2012).

Measurement of SWCCs can be done using numerous types of test equipment and procedures. The most common devices are the Tempe cell, pressure plate extractors, Fredlund pressure plate cell and modified triaxial cells (described later). In addition to direct measurement, the SWCCs can also be estimated. Since the SWCC is mainly related to the voids in the soil structure and the water content in the voids, many studies have been conducted to estimate the SWCC from the grain-size distribution curves of the soil as well as their plasticity index. Figure 9 shows SWCC prediction models for both plastic and non-plastic materials (Zapata, 1999).

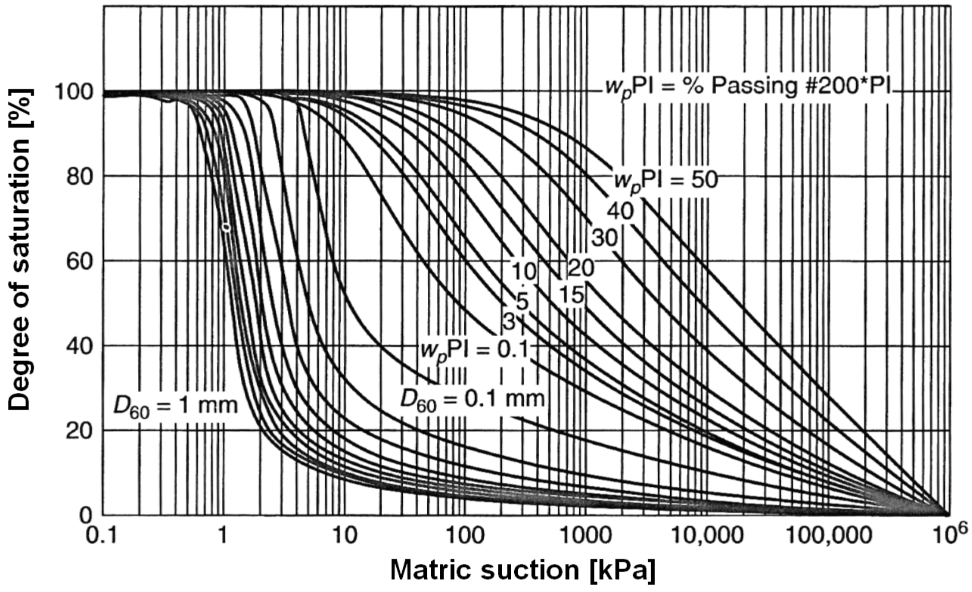

Figure 9. SWCCs for both plastic and non-plastic materials (modified after Zapata, 1999).

The constitutive equations for unsaturated soil properties can be rewritten by incorporating the matric suction into the modelling using the SWCCs. As unsaturated soil properties are primarily a function of the moisture content of the soil and moisture is the main environmentally driven variable that directly affects material mechanical properties of unfrozen unbound materials, suction effects can therefore be coupled to the material response characterization.

4. Moisture Influence on Pavement Performance and Bearing Capacity

In pavement engineering, it is generally recognized that the presence of excess moisture content in unbound pavement materials, especially when combined with heavy traffic loads, can result in accelerated pavement deterioration and significant reduction in service life (ARA, 2004; Berntsen and Saarenketo, 2005; Erlingssson, 2010). The moisture related deterioration mechanisms greatly depend on the type of pavement structure, the material, the topography of the section, the climate and the condition of the pavement surface. In thin flexible pavement structures, unbound granular layers and subgrade soils undergo higher traffic load stresses. Since unbound pavement materials are generally sensitive to moisture content, thin pavement structures show higher sensitivity to moisture variations. Thus, their performance is highly dependent on their moisture condition and prolonged exposure to high moisture content can result in pavement instability and large resilient and accumulated permanent deformations. This highlights the significant role of maintaining an intact surface course with a functional drainage system.

However, thicker flexible pavement structures are usually exhibit less sensitivity to moisture content variations due to the fact that lower stress levels are experienced by the unbound layers (Huang, 2003) due to surface traffic loads. Nevertheless, high moisture content can still indirectly contribute to pavement deterioration. High moisture content in unbound layers which results in softer support to the asphalt concrete course leads to higher tensile stresses at the bottom of this layer caused by the traffic load. This in return will accelerate crack propagation in the asphalt concrete layer which will then allow for surface water infiltration to the pavement structure (Cedergren, 1988).

In concrete pavement systems, the water related deteriorations are mainly concentrated around the slab joints and edges if water is present at the slab and supporting layer interface (Hansen et al., 1991). Along the joints, water pressure can locally increase under traffic load passages, resulting in movements of water with high velocity which can causes erosion in the slab edges and the supporting unbound layers.

4.1. Mechanism of moisture related material deterioration and degradation

In coarse-grained aggregate materials, the pores between the particles are relatively large. Under draining conditions, the load bearing mechanism of the material is mainly based on particle contact stresses and their inter-particle friction. Introduction of water to the material can usually result in reduction in the inter-particle frictional strength and therefore larger resilient and accumulated permanent deformations under traffic loading. If water fills in all the voids between the aggregate particles (non-draining condition) the pore water may be pressurised under traffic loading. The water pressure counteracts the particle contact stresses, which can result in considerably reduction in the material strength (Dawson and Kolisoja, 2004).

In fine-grained materials and subgrade soils, the undesirable effect of excess moisture presence is more significant. Besides the water lubrication effect, an increase in moisture content results in a decrease in the soil mass suction and therefore reduction in the effective stress (Sawangsuriya et al., 2008; Yang et al., 2008; Cary and Zapata, 2010 and 2011). In the unsaturated state where pores are no longer completely filled with water, the soil suction parameter and its contribution to the effective stress can be introduced to describe the mechanical behaviour of the material. In this case, the effective stress, which is the function of external stresses and internal forces including the contractile water skin effects, is taken into account. This approach converts a four-phase porous medium to a mechanically equivalent single phase using nonlinear mathematical models that allow for considering moisture variation effects on the mechanical behaviour of materials. These constitutive models include the effect of suction and moisture pressure within the soil and aggregate mass (Laloui et al., 2009).

4.2. Seasonal variation in thin flexible pavements structural stiffness

Most of the thin flexible pavement structures in cold regions experience considerable seasonal variations in stiffness (Simonsen and Isacsson, 1999). The conceptual overall seasonal variation in bearing capacity of the pavements in cold regions includes a significant increase in stiffness during the winter period. Besides the stiffness variation of the asphalt concrete layer due to seasonal temperature changes, pavement unbound materials also exhibit considerable seasonal variations due to the freezing and thawing effects (Saarenketo and Aho, 2005).

Frost penetration in the pavement structures creates strong bonds between the unbound particles as the moisture surrounding the particles freezes. This results in a very stiff matrix of granular material and subgrade soil particles (Simonsen et al., 2002). Therefore, during the frost period, pavements exhibit high overall stiffness and can usually support heavy traffic axle loads without any problem. This increase in the overall stiffness of the pavement system due to frost penetration depends on many factors such as the depth of the frost zone, material properties and the pre-freezing moisture content.

The frost depth and length of the frost period depends on the geographical position and the climate of the road section. This condition usually lasts throughout the winter period. However, short thawing periods can occur if the air temperature rises above zero degrees Celsius (0°C). The surface intermittent thawing can penetrate up to a few decimetres in depth and cause a temporary decrease in the unbound granular layer stiffness. The length of the surface thawing can vary from a few hours up to a few days, depending on the weather condition. As the air temperature drops to below freezing temperature, the surface thaws refreeze and the layers regain their high stiffness.

The major thaw weakening phase, often referred as structural thaw weakening, occurs when thawing penetrates deeper into the pavement structure or in the subgrade soil. During this period all the segregation ice lenses that were generated during the freezing period convert back into the liquid form as the temperature deeper in the pavement structure rises to above freezing values. A considerable amount of excess moisture is usually released in the pavement structure. Since thawing is a top-bottom process, the moisture content of the thawed sections above the thawing ice lenses can be significantly high since draining paths are trapped (Simonsen and Isacsson, 1999; Saarenketo and Aho, 2005). As this section is surrounded by the asphalt concrete layer at the top and the thawing ice lenses at the bottom, hydrostatic pore pressures can be built up due to heavy traffic load passages. This can cause pumping of the fines of the material as moisture flows to the sides and therefore loss of support.

The spring-thaw period is usually followed by a "recovery" period during which the bearing capacity of the pavement system is recovered. In granular base and subbase layers, the stiffness of the material is usually regained shortly after the spring-thaw period is over as the excess moisture drains and the layer recovers. This is due to the relatively high permeability in the granular materials. However, in subgrade soils, the recovery period usually takes place over a much longer time, especially if the fines content of the material is high (e.g. moraines, silty and clayey materials). Full recovery of subgrade soils can take from a few weeks up to a few months, depending on the material permeability and the drainage condition of the pavement structure. Figure 10 illustrates the principal changes in overall stiffness of pavements in cold regions.

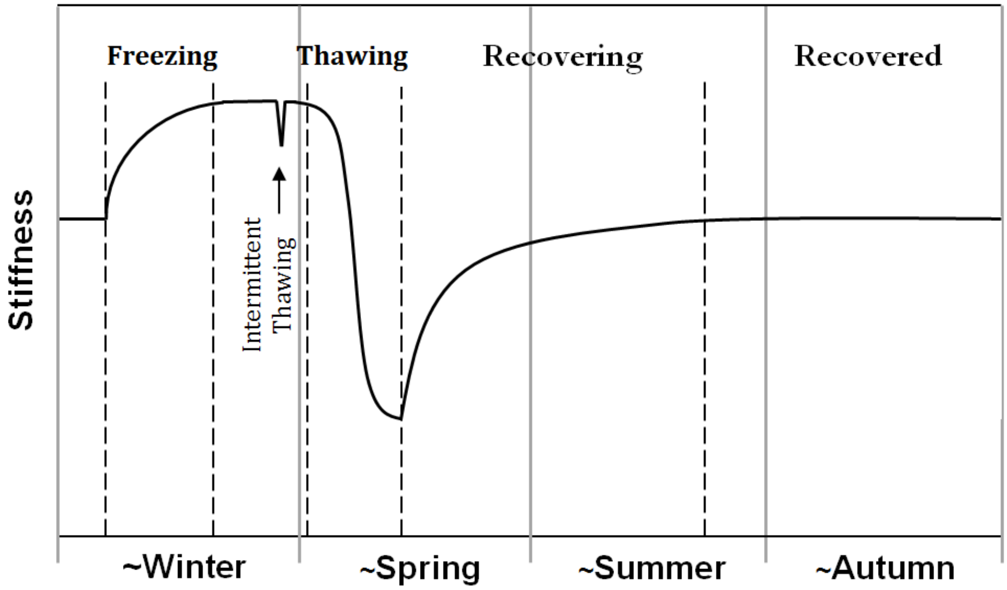

Figure 10. Conceptual pavement stiffness variations due to freezing and thawing.

5. Mechanical Behaviour of Unbound Materials and Subgrade Soils

5.1. Laboratory investigation and measurements

The mechanistic pavement design and analysis often require substantial data on the properties of pavement materials and their mechanical response to external loads. For pavement unbound materials and subgrade soils, these material properties are mainly related to the stiffness, durability and stability of the material. The test methods often used consist of investigating the mechanical behaviour of the material under repeated loading, simulating the effect of the traffic loads under controlled temperature and moisture conditions that can be experienced by the material in the field. Similar to the traffic induced stresses, the applied cyclic loads are rather small compared to material strength; however they are usually applied for a large number of times.

The mechanical deformation of pavement unbound materials under repeated small loading can be divided into two parts: the recoverable deformation and the accumulated plastic deformation. After each load application, the material usually experiences some deformation that does not recover. The permanent deformation, often known as the plastic deformation, is generally observed during the early stages of load application. After a sufficient number of load applications, the deformation almost completely recovers and the contribution to plastic deformation becomes very small or negligible. The deformation that is totally recovered during the load application is usually used to determine the stiffness properties of the material. Figure 11 shows the typical behaviour of unbound materials under cyclic loading.

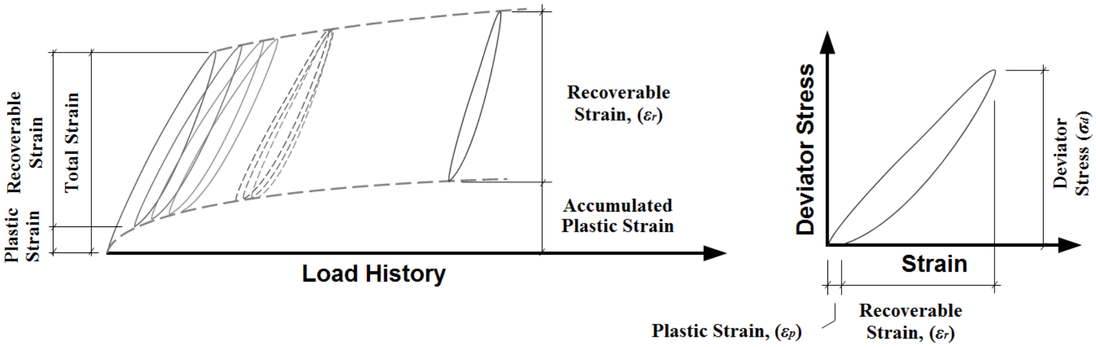

Figure 11. Deformation behaviour of unbound materials under repeated load (left) and stress-strain curve during one cycle of load application (right).

5.2. Resilient modulus of unbound materials

The stiffness property of unbound granular materials and subgrade soils is widely characterized using the resilient modulus parameter (M_R). This parameter is generally defined using Repeated Load Triaxial (RLT) tests. In conventional resilient modulus test using RLT testing, the material is compacted into cylindrical specimens at the degree of compaction and moisture contents occurring in the field. The specimen that is enwrapped in a latex membrane is then confined by pressurising the test chamber using air, water or oil and exposed to cyclic axial deviator stresses. Usually, series of computer-controlled cyclic axial deviator stresses are applied to the specimen using the piston attached to the top loading platen, and the axial deformation is recorded. Axial deformations are either measured using fixed gauges on the loading piston and out of the pressurised chamber or using gauges that are directly mounted on the specimen. Figure 12 shows the principles of the resilient modulus test suing RLT test.

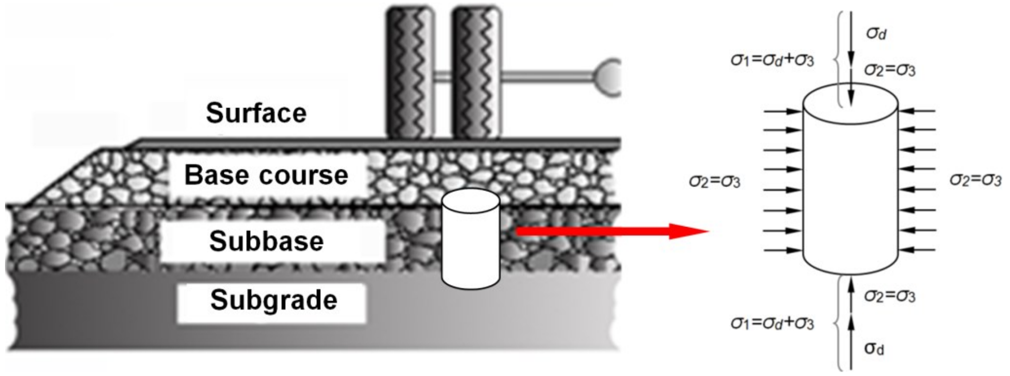

Figure 12. Principles of the RLT test.

Using the cyclic deviator stress (σ_d or q) and the measured axial recoverable strain (ε_r), the resilient modulus is then defined as:

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad [2]$$

In a constant confined RLT test, the deviator stress (σ_d) is the cyclic axial stress applied on the specimen in addition to the constant confinement pressure of the triaxial chamber ($\sigma_c = \sigma_2 = \sigma_3$) that is applied to the specimen in all the directions.

Above all the other influential factors (discussed later), the resilient modulus is highly dependent on the state of stress of the material. The state of stress of the material is usually expressed by the bulk stress (θ), where $\theta = (\sigma_1 + \sigma_2 + \sigma_3)$ or the mean normal stress (p) where $p = \theta/3$. The σ_1, σ_2 and σ_3 are the principal stresses.

Stress dependent behaviour of pavement unbound material from laboratory measurements

There are many factors that influence the mechanical properties of pavement unbound materials and subgrade soils. Lekarp et al. (2000) conducted an extensive literature review on the resilient modulus of unbound materials and the different factors that can affect the resilient modulus. According to this survey the resilient modulus of unbound materials may to different degrees be affected by the stress state, material density, grain size distribution and particle shape, stress history and moisture content. From the literature it is known that the material stress state is certainly the most significant factor that can affect the resilient modulus property of unbound materials (Hicks and Monismith, 1971; Rada and Witczak, 1981; Uzan, 1985; Kolisoja, 1997). Many studies on the mechanical response of unbound materials have shown that the resilient modulus property is highly dependent on the confinement pressure and sum of the principal stresses. An increase in confining pressure and the sum of the principal stresses result in a considerable increase in the resilient modulus. However, the deviator or the shear stress has a much less significant influence on the material stiffness. In coarse-grained granular materials, change in deviator stress had no or insignificant influence on the stiffness of the material (Lekarp et al., 2000). The effect of the deviator stress on the resilient modulus seemed to be very much dependent on the material type, compaction and the deviator stress level itself. In a study conducted by Hicks and Monismith (1971) minor softening behaviour of the material was observed at low stress levels while minor hardening behaviour was observed at higher stress levels. Hicks (1970) stated that the resilient modulus is in practice independent of the deviator stress level if no plastic deformation is experienced. This implies that the resilient modulus stress-dependent behaviour of coarse-grained granular materials can sufficiently be captured by only using the first stress invariant.

In fine-grained materials and subgrade soils, the resilient modulus usually decreases with increase in the deviator stress. The softening behaviour in the material due to increase in the deviator stress level is assumed to be related to increase in the shear stress, which softens the material and thus yields to a lower resilient modulus (Drumm et al., 1990; Li and Selig, 1994; Muhanna et al., 1999).

The significant impact of the stress state on the resilient modulus of unbound materials has resulted in the development of a number of constitutive models that mathematically describe the material stress-strain relationship. Most of these models describe the resilient modulus stress dependency using different stress state variables (Lekarp et al., 2000) and are mainly developed through curve fitting and nonlinear least square regression methods using RLT test data. A comprehensive analysis and evaluation of the resilient modulus models can be found in Andrei (2003), Lekarp et al. (2000), Rada and Witczak (1981) and Kolisoja (1997).

Among all the available stress dependent resilient modulus models, the generalized constitutive model proposed in the *Mechanistic-Empirical Pavement Design Guide* (ARA, 2004) has gained popularity and been widely used over recent years. This model accounts for the stress dependent behaviour of the resilient modulus through a three-dimensional stress state function. It captures the overall stress-hardening behaviour of unbound aggregates through the bulk stress parameter and stress-softening behaviour of fine-grained soils due to shear stresses through the octahedral shear stress. This model is expressed as:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \qquad [3]$$

where M_R is the resilient modulus, θ is the bulk stress (sum of the principal stresses), p_a is the atmospheric pressure, τ_{oct} is the octahedral shear stress, $\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$, σ_1, σ_2 and σ_3 are principal stresses and k_1, k_2, k_3 are model parameters obtained from the regression of the resilient modulus data. A simplified version of the constitutive model expressed in Equation 3 is the $k - \theta$ model (Seed et al., 1967) given in the following equation:

$$M_R = k_1 \theta^{k_2} \qquad [4]$$

where k_1 and k_2 are model regression constants and θ is the bulk stress. This model accounts for material stiffness stress dependency solely by bulk stress (sum of the principal stresses). This oversimplification results in certain drawbacks when modelling the material resilient behaviour. The main shortcoming is that it does not directly account for the shear strains induced by the deviator stress (May and Witczak, 1981). The role of shear stresses in the resilient modulus property is particularly significant in fine-grained materials and subgrade soils. However, application of simplified $k - \theta$ can still be appropriate in capturing the stress dependent behaviour of coarse-grained granular materials (Huang, 2003).

M$_R$ *models incorporating subgrade soil suction*

As unbound granular layers and upper part of the subgrade are frequently in partially saturated conditions, resilient modulus models that accounting for the unsaturated state (i.e. incorporating soil matric suction) have gained interest over the past years. Comprehensive understanding and characterization of unsaturated soils generally require the measures of stress state variables. As proposed by Fredlund and Rahardjo (1987), the resilient modulus of unsaturated soils can be described using a function of three stress variables, as given in Equation 5.

$$M_R = f\left[(\sigma_1 - \sigma_3), (\sigma_3 - u_a), (u_a - u_w)\right] \qquad [5]$$

where $(\sigma_3 - u_a)$ is the net confining stress, $(\sigma_1 - \sigma_3)$ is the deviator stress (σ_d) and $(u_a - u_w)$ is the matric suction (ψ_m). σ_3, σ_1, u_a and u_w are confinement pressure, axial cyclic deviator stress, pore-air pressure and pore-water pressure, respectively.

A number of studies have been carried out to investigate the effect of moisture content on the resilient response of pavement unbound materials using matric suction and proposed several suction-resilient modulus models (Parreira and Goncalves, 2000; Khoury and Zaman, 2004; Yang et al., 2005; Liang et al., 2008; Cary and Zapata, 2011, Ng et al., 2013). These studies have shown that there is often a strong correlation between the matric suction and the resilient modulus.

Advanced suction-controlled RLT testing

Conducting suction-controlled RLT tests requires more advanced triaxial cells and control unit. The specimen preparation and the tests itself are also more complex and time consuming compared to the conventional RLT tests. The triaxial cells that are capable of measuring matric suction throughout the test are generally designed with independent measurement/control the pore-air and pore-water pressures of the specimen during the conditioning and the testing phase. The axis translation technique is usually applied for conducting the RLT tests. The common practice is to measure/control the pore-water pressure using HAE ceramic disks that are embedded into the bottom pedestal and top loading platen of the cell and independently measure/control the pore-air pressure from the top loading platen (see Figure 28).

Field investigation and measurements

In situ evaluation of pavement structural capacity and functional condition has become an inevitable part of road network pavement management systems during the past few decades. This has led to development of a variety of non-destructive test methods and equipment throughout the years. The structural capacity of a pavement structure using a non-destructive test method is usually assessed by measuring the surface deflections under a controlled loading sequence. This testing procedure and equipment are designed to simulate the traffic loading as close to reality as possible. These measurements are usually carried out for quality control, unbound layers stiffness and compaction assurance, identification of weak sections, road structural strengthening, and imposing load restrictions as well as for research purposes.

The Falling Weight Deflectometer (FWD) device is one of the most widely used types of equipment in measuring the mechanical response of the pavement systems under dynamic load (Tayabji and Lukanen, 2000; Irwin, 2002). Most of the commonly used modern FWD equipment consists of three major components: the loading unit that is usually composed of a falling weight being dropped from a certain height on a circular plate to generate the defined load impact, a measuring system consisting of several deflection sensors (accelerometer or geophone) measuring the pavement surface deflection at certain distances from the loading plate and the data acquisition systems (Figure 13). The loading unit is designed to produce load pulses that stimulate the loading effect of heavy traffic passage under a normal travelling speed using a combined two-mass and buffer system. The FWD loading system usually produces is a haversine shape load pulse with an approximate duration of 0.03 seconds. The maximum measured deflection of each sensor due to the impact loading is considered to reproduce the deflection bowl or deflection basin of the measurements.

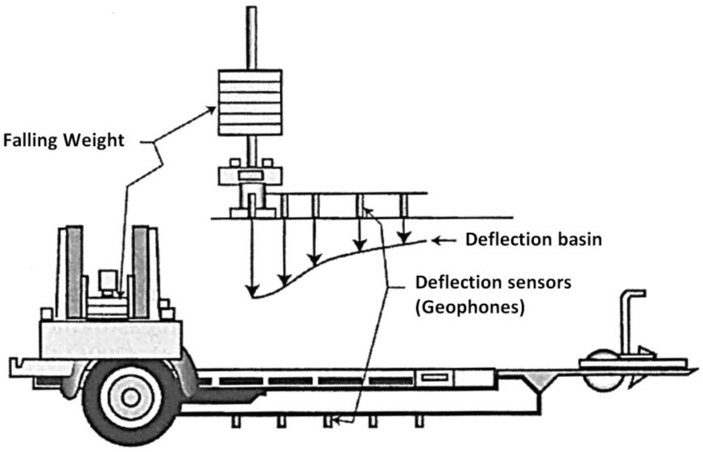

Figure 13. Schematic overview of a Falling Weight Deflectometer and its components (Doré and Zubeck, 2008).

The magnitude and the shape of the deflection basin under a given load pulse can be used as a representative for the material properties of pavement system layers and their overall stiffness. It is generally accepted that deflections at some distance from the plate load centre may be correlated to the deformation at a corresponding depth beneath the road surface (Mork, 1990). This denotes that deflections close to the centre of the load plate reflect the material properties of the pavement layers, while deflections sufficiently away from the load centre only reflect the subgrade properties.

Generally, the data from FWD measurements is analysed at two different levels: the first level of analysis includes deflection basin analysis or deflection basin shape indicators. These indices are good indicators for a fast and preliminary assessment of the pavement structure and to sort out the weak sections along the road. The seasonal climatic effects on pavement overall response and material stiffness can generally be perceived using the deflection bowl and deflection basin indices. For instance, in pavements exposed to freeze and thaw cycles, depending on the thawing progression in the pavement structure, the deflection basin changes in both the shape and the size (Simonsen, 1999). In early spring, the pavement is in a fully frozen state, the deflection basin is narrow and the measured deflections are very small. As thawing penetrates the pavement structure, the deflection basin widens and increases in depth. The maximum basin deflection is observed at the end of the spring-thaw period or within a few days after the thawing is completed, in which the subgrade is usually in a very wet condition.

The second level of FWD data analysis includes estimation of the stiffness or resilient modulus of the pavement layers through backcalculation procedures. This is a more advanced procedure that is usually used in the mechanistic based evaluation of pavement structures. This technique applies the multi-layer elastic theory and models.

In backcalculation, the FWD impact load, pavement structure layer thicknesses, material Poisson's ratio and the measured surface deflections are assigned as the inputs of the procedure. Using the multi-layer elastic theory, a set of pavement layer moduli that would theoretically produce the measured deflection basin with a certain level of errors is determined. The backcalculation is an iterative procedure from the simple equivalent thickness approach to more sophisticated approaches that apply least-square optimization methods.

It should be noted that special concerns should be taken into account when performing backcalculation on pavements that are exposed to significant environmental variations such as moisture content variations due to groundwater fluctuations or pavements that are exposed to frost-thaw actions. Conduction quality backcalculation regarding these pavements usually requires substantial information on depth to the frozen layers, the temperature gradient of the asphalt concrete layer, moisture distribution within the unbound layers and depth the groundwater and/or bedrock. For this purpose, pavement instrumentation can be taken as collecting data on the climatic condition of pavement structures and their induced stresses. Pavement instrumentation and intensive data collection can be a valuable enhancement for a better understanding of factors influencing pavement behaviour and response and both their short term and long term impacts. However, intensive data collection, management and analyses are usually expensive and time consuming and therefore are mainly limited to research purposes.

Stress dependent behaviour of pavement unbound material from field measurements

The nonlinear stress dependent behaviour of pavement unbound materials has traditionally been determined from laboratory-based studies using RLT testing due to its manageability and relative simplicity as well as time and cost efficiency. Even though RLT testing is designed to simulate the internal in situ loading and environmental condition of pavement materials and subgrade soils, it might still not be fully capable of reproducing the internal structure, overburden pressure and traffic induced stress states (Karasahin et al., 1993; Ke et al., 2000).

Non-destructive testing such as FWD and Seismic Pavement Analyser (SPA) measurements are probably the most effective methods to capture the in situ behaviour and response of pavement materials and structures. FWD measurements and backcalculation of pavement layer moduli are in particular cost efficient and well-recognised methods for structural evaluation of pavement systems that are widely used by the road authorities. The ability of the FWD to stimulate traffic loading, its mobility and capacity to collect large amounts of data at network level have gained interest among the pavement community for more advanced analysis of FWD data. This is along the path towards development of mechanistic-empirical design framework for pavement systems that requires improved knowledge about the materials, climatic factors, geometry and traffic on pavements structural response and performance.

Even though most pavement unbound materials exhibit nonlinear stress dependent behaviour, they are traditionally treated as linear elastic materials in backcalculation of FWD data. A majority of the backcalculation programs apply the simplified multilayer linear elastic theory to backcalculate pavement layer stiffness. However, realistic analyses of deflection data may require more advanced backcalculation techniques that account for material nonlinearity.

Over the years, several studies have been conducted to evaluate the nonlinearity of pavement material from deflection basins. Uzan (2004) applied both linear and nonlinear procedures to analyse the FWD data obtained from an instrumented test site in Hanover, New Hampshire. In his study, the backcalculation of the data exhibited superior fit to the deflection bowl when the nonlinear approach was implemented in comparison with the linear approach. This was in agreement with the stress and strain measurements from the site instrumentation that also confirmed the nonlinear response of the pavement material.

Meshkani et al. (2003) investigated the feasibility of backcalculating flexible pavement layer nonlinear parameters from FWD and SPA testing. They used four hypothetical pavement sections with nonlinear base and subgrade materials to study the feasibility and accuracy of backcalculating the nonlinear parameters from deflection bowls. Although nonlinear parameters for thinner pavement structures could be estimated, they concluded that in many cases the deflection bowl did not provide sufficient information to reliably backcalculate the nonlinear parameters.

Steven et al. (2007) modelled a thin-surfaced flexible pavement structure that was instrumented with strain gauges and pressure cells using the Finite Element (FE) method in ABAQUS computer code. In their FE model, both the granular layer (anisotropic) and subgrade (isotropic) were modelled using the generalized nonlinear constitutive model as expressed in Equation 3. The material model parameters used in the FE model were obtained from RLT testing. They calibrated their model so that the measured and calculated stresses and strains levels agreed within the acceptable tolerance. The computed surface deflection from the FE model and the surface deflections measured FWD at the test section showed an excellent match for all the FWD load levels. They concluded that a fully nonlinear pavement model can realistically represent the response of the pavement structure during the FWD tests. A similar conclusion was also made in a study conducted by Uzan (1994).

In 2005, Li and Baus conducted a full-scale static and cyclic plate load test to investigate the mechanical properties of unbound granular materials and the effect of moisture content. Based on the plate load measurements, they developed a procedure to backcalculate the material nonlinear parameters of the $k-\theta$ model that was implemented in the algorithm.

5.3. Permanent deformation of unbound materials

The plastic response and consecutive accumulation of permanent deformation of unbound materials under repetitive traffic loading is also a complex phenomenon and depends on many factors with different degrees of significance. The main influential factors are: stress state, number of load cycles, reorientation of principal stresses, loading history, moisture content, grain size distribution, degree of compaction and fines content (Lekarp et al., 2000).

The permanent deformation development in fine-grained materials under repeated traffic loads can be mainly associated with three different mechanisms. These mechanisms are the cumulative compaction, cumulative plastic shear strain (distortion of material fabric) and cumulative consolidation (Li and Selig, 1996; Werkmeister et al. 2004). The development of permanent strains of unbound materials under repeated cyclic loads can be described using the shakedown concept (Sharp and Brooker, 1984). According to Werkmeister et al. (2001 and 2004) the permanent strain accumulation of unbound materials under repeated cyclic loads can be classified into three categories, namely; Range A: the plastic shakedown, Range B: the intermediate response or plastic creep and Range C: the intermediate collapse (Figure 14).

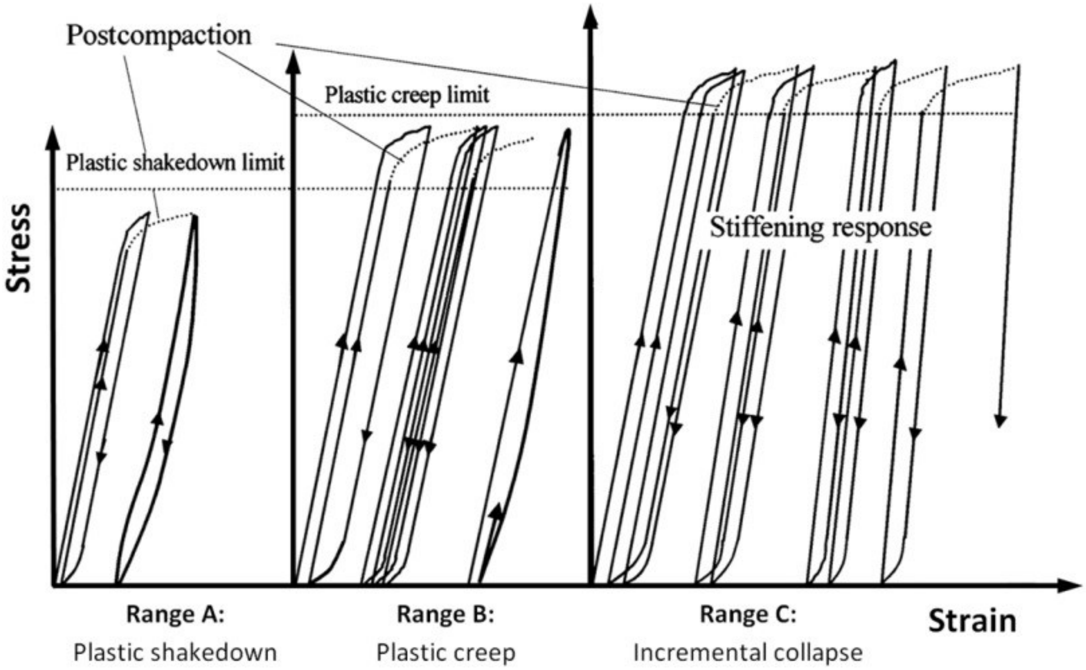

Figure 14. Theoretical behaviour of unbound materials under repeated cyclic load (modified after Werkmeister et al., 2001).

From a pavement engineering perspective, unbound layers should preferably not undergo stress levels higher than the plastic shakedown limit. Under this condition, the permanent strains would cease after a sufficient number of load applications and only minor accumulation of permanent deformation would take place. The exposure of unbound materials to stress levels higher than the plastic shakedown limit (Range B) should be restricted to only occasional cases and stress level higher than the plastic creep (Range C) should never occur as it can cause severe rutting and structural failure in the pavement system (Erlingsson and Rahman, 2013).

Modelling permanent deformation of pavement unbound materials

In practice, the permanent deformation characterization of pavement unbound materials is generally studied by conducting RLT tests. However, due to the time consuming nature of permanent deformation tests, it has been less studied compared to the resilient behaviour of the material.

In spite of this, over the past few years several research has been conducted to develop test procedures and outline prediction models for permanent strain characterization of pavement unbound materials through RLT tests. The permanent deformation models can be generally divided into two different categories: empirical relationships describing the influence of the number of load applications or level of stress (or a combination of them), and elastoplastic models (Lekarp et al., 2000; Hornych and El Abd, 2004). Most of the established models were originally developed based on tests from single stage RLT test procedures. These models can be generally described as follows:

$$\hat{\varepsilon}_p(N) = f_1(N) f_2(p, q, \varepsilon_r) \qquad [6]$$

where N is the total number of load cycles, p is the hydrostatic stress, q is the deviator stress.

In the single stage RLT based models a certain number of load applications are applied only under a constant cyclic stress condition. However, the material in the field generally experiences traffic load pulses with different magnitudes. Thus, a more realistic and practical simulation approach would be to conduct a series of different stress paths on a single specimen (multistage RLT tests). Modelling the permanent deformation behaviour of the material to cover the entire range of the stress paths therefore requires certain modification of the discussed models to accommodate the time-hardening concept (Lytton et al., 1993; Erlingsson and Rahman, 2013).

In the time-hardening concept (Figure 15), the accumulated permanent strain from the preceding loading history is used to calculate the number of load cycles required so that the same amount of accumulated permanent strain in the current stress path (stress path i) is obtained. This is called the equivalent load cycle (N_i^{eq}). The N_i^{eq} for a certain stress path i is used to transform the total number of load cycles (N) from the beginning of the test so the stress path i alone attain the equal deformation that is accumulated from all the preceding stress paths. The N_i^{eq} is then used to adjust the total number of load cycles, N , applied from the beginning the test to calculate the effective number of load cycles ($N - N_{i-1} - N_i^{eq}$). N_{i-1} is the total number of load cycles at the end of the $(i-1)$ stress path. The subscript i refer to the i^{th} stress path. Thus, using this concept, it is possible to model the whole range stress paths from the multistage RLT tests (Figure 15).

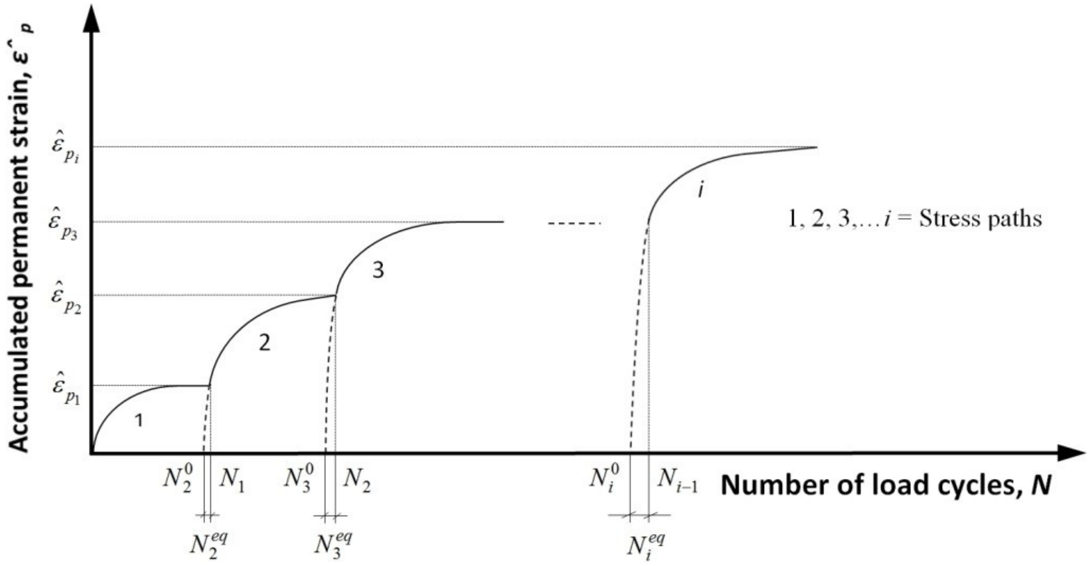

Figure 15. Schematic demonstration of the time-hardening concept (Erlingsson and Rahman, 2013).

If the time-hardening concept is applied to the generalized single stage permanent deformation model (given in Equation 6), the following generalized equation for multistage RLT tests is obtained:

$$\hat{\varepsilon}_{pi}(N) = f_1(N - N_{i-1} + N_i^{eq}) f_2(p_i, q_i, \varepsilon_{r_i}) \qquad [7]$$

In this approach, the data from a multistage RLT test on a single specimen can be used to obtain the optimized set of material parameters for the selected permanent deformation model.

6. Moisture Effects on Unbound Materials and Subgrade Soils

Unbound granular materials and subgrade soils significantly contribute to the overall bearing capacity of pavement structures. The material characteristics of unbound layers and subgrade soils are therefore of great importance in the performance of pavement systems. Although pavement systems are ideally designed to remain as drained as possible, moisture is usually present in pavement structures and the unbound layers are often in a partially saturated state. Even pavement structures with good drainage systems can experience periods with excess moisture presence such as (e.g. heavy rain events and a spring-thaw period in cold regions).

The significant detrimental effects of moisture content on the behaviour of unbound materials are well-known (Cary and Zapata, 2010; Erlingssson, 2010; Saevarsdottir and Erlingsson, 2013a). In coarse-grained granular materials an increase in moisture content can result in reduction in the resilient modulus due to decreased contact friction and particle interlock strength (Lekarp et al., 2000; Ekblad and Isacsson, 2006). In fine-grained materials and subgrade soils, in addition to the lubricating effect, pore water usually affects the effective stress of the soil structure due to a decrease in pore suction which will result in decreased reduction in material stiffness. In materials with low permeability that are exposed to frequent heavy traffic stress loads, pore pressure build-up may also take place which can result in considerable bearing capacity loss (Yang et al., 2008; Cary and Zapata, 2011; Nowamooz et al., 2011). All other factors remaining unchanged, an increase in moisture content results in larger resilient and plastic strains and accelerate the rate of distresses in pavement structures (ARA, 2004). Pavement moisture content and its influence on the behaviour of unbound materials has been the subject of many laboratory-based and field investigations. Some of the moisture related studies found in the literature are presented below.

6.1. Laboratory-based investigation and measurements

Conventional repeated load triaxial testing

In pavement engineering, the mechanical response of the pavement materials are traditionally characterized using the total stress approach. In spite of the fact that pavement unbound layers are usually in partially saturated conditions, the effect of soil suctions is not generally considered. At laboratory scale, the material mechanical response is widely characterized using RLT tests. When using the conventional total stress approach, the effect of moisture content on the mechanical behaviour of unbound materials is generally taken into account later in the design process using adjusting models (described later).

Ekblad and Isacsson (2006) investigated the influence of moisture on the resilient properties of coarse-grained granular materials with different grading using a large scale triaxial cell. They monitored the moisture content of the specimen using two TDR probes buried in the specimen. They reported a significant loss in the resilient modulus with increase in moisture content, particularly in specimens with high fines content. The effect of moisture content on the resilient modulus was considerably less in specimens with coarser grading.

Andrei (2003) conducted an extensive laboratory test program using the RLT method for both coarse-grained and fine-grained materials. The materials used in the study consisted of four base and four subgrade materials that are typically encountered in Arizona. The RLT tests were conducted at different moisture contents and compaction degrees to develop a resilient modulus predictive model that could estimate changes in the resilient modulus as a function of compaction degree, stress level and moisture content. Considerable changes in the resilient modulus were observed due to moisture content variations. Plastic subgrade materials were in particular very sensitive to moisture and the resilient modulus variations from 14 to more than 1350 MPa were observed due to changes in moisture content. However, for non-plastic soil and base material, the impact was much less. These materials exhibited up to three times higher resilient modulus values as the moisture content was reduced compared to the optimum moisture content.

M_R-Moisture adjustment models

Several models have been developed to incorporate the effect of moisture content and its variations when predicting the resilient modulus of unbound pavement materials. Most of the developed models are based on laboratory testing of unbound materials at differing moisture contents.

A simple approach that has gained popularity over the recent years is the predictive M_R-Moisture model proposed in *Mechanistic-Empirical Pavement Design Guide* (ARA, 2004). This one-dimensional model directly incorporates variations in the moisture content to the resilient modulus of unfrozen unbound materials using an adjustment factor given as the following:

$$\log\frac{M_R}{M_{R_{opt}}} = a + \frac{b-a}{1+\exp(\ln(-b/a)+k_s(S-S_{opt}))} \qquad [8]$$

where $M_R/M_{R_{opt}}$ = resilient modulus ratio; M_R is the resilient modulus at a given time and $M_{R_{opt}}$ is the resilient modulus at a reference condition. Further is a = minimum of $\log(M_R/M_{R_{opt}})$, b = maximum of $\log(M_R/M_{R_{opt}})$, k_s = regression parameter and $(S-S_{opt})$ = variation of degree of saturation expressed in decimal.

This empirical model and its regression parameters were developed through extensive laboratory triaxial tests conducted by Andrei (2003). Figure 16 shows the M_R-Moisture model for both the fine-grained and coarse-grained materials proposed in MEPGD.

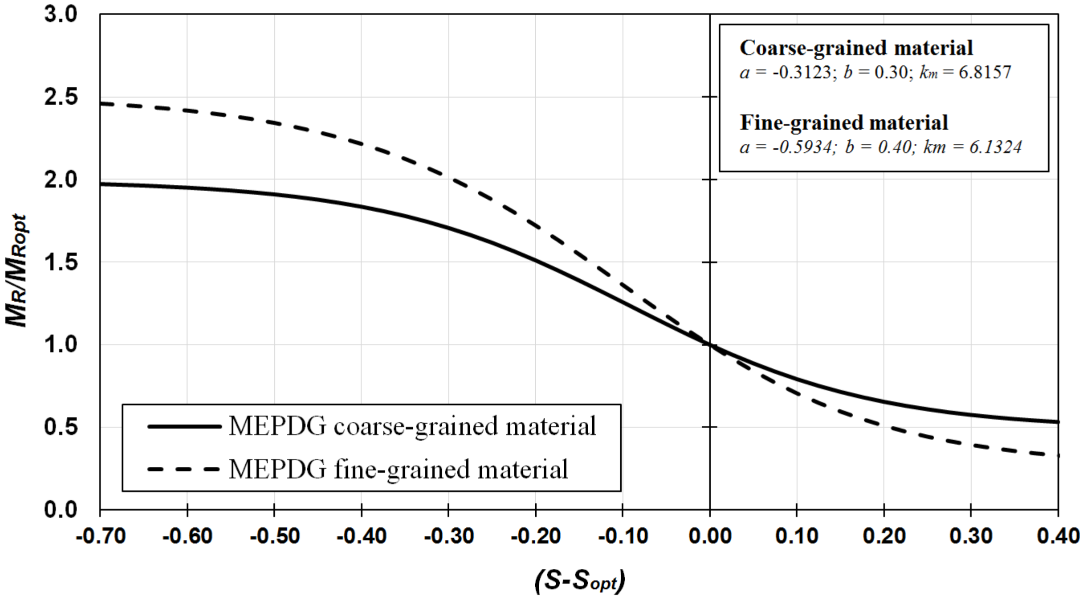

Figure 16. M_R-Moisture model proposed in MEPDG (ARA, 2004).

Full-scale accelerated pavement testing

Erlingsson (2010) conducted a study based on Accelerated Pavement Testing (APT) of an instrumented thin flexible pavement to investigate the influence of the moisture content on the performance of the pavement structure. In this study 1000,000 wheel load passages were applied using a Heavy Vehicle Simulator (HVS) on a typical flexible pavement structure in which 500,000 of the load passages were conducted while the pavement structure was in its natural moisture condition and 500,000 load passages were conducted after the groundwater table was raised to 30 cm below the top of the subbase. From the measurements and the numerical analyses of the data it was observed that introducing the water to the system resulted in larger permanent and resilient strains in all the unbound layers. In similar studies by Saevarsdottir and Erlingsson (2013a and 2013b), it was also observed that all the unbound layers showed increased permanent and resilient deformations as the moisture content increased, with the most dramatic increase in the subgrade layer.

6.2. Field-based investigation and measurements

The considerable influence of environmental factors on the performance of pavement structures has led to significant effort in in situ measurement of these parameters. Several highway agencies around the world have initiated seasonal monitoring data collection as part of their Long-Term Pavement Performance (LTPP) programs to determine climatic factor effects on performance of pavement systems. These data bases can consist of weather stations data, pavement moisture content and temperature profile monitoring as well as frost penetration and frost-heave measurements (Jong et al., 1998; Janoo and Shepherd, 2000; Erlingsson et al., 2002; Savard et al., 2005; Zapata et al., 2009).

In an 18-month field survey on three instrumented highways in the state of Wisconsin, Jong et al. (1998) monitored the pavement moduli changes caused by seasonal climatic variations. They reported up to 4 and 12 times increase in the subgrade and base layer moduli, respectively, as frost penetrated into the pavement structure. They observed a clear correlation between the in situ moisture content and the stiffness of unbound layers. The base and subgrade layer moduli were decreased by 35 and 65 percent, respectively, due to an increase in the moisture content at the end of the thawing period compared to the pre-freezing measurements.

Janoo and Shepherd (2000) analysed the subsurface moisture and temperature data as well as the surface deflection measurements collected from ten sites across the state of Montana to measure in situ subgrade moduli and their seasonal variation. Significant variation in unbound layer moisture content and layer moduli was observed from the field measurements. Using the deflection data, they recommended a model that could predict the subgrade stiffness as a function of temperature and volumetric moisture content to be used in future mechanistic design practices. They also suggested critical load-restriction time periods during spring-thaw weakening based on the temperature and moisture measurements.

In a field study conducted by Erlingsson et al. (2002), temperature and moisture variability of three road sections in south-west Iceland were monitored during a three year period. A significant long and short term volumetric moisture content variation was observed due to the freeze-thaw conditions and the precipitation. The layer moduli backcalculation from the FWD showed a strong correlation with the measured moisture content.

7. Summary of the Papers

7.1. Paper I and II

The appended papers present environmental data measurements, analyses and findings from the field studies carried out in the Torpsbruk test site along county road 126 in southern Sweden (Figure 17). The pavement structure consists of a 100 mm thick HMA layer (dense graded mix, 16 mm maximum grain size and 160/220 bituminous binder penetration grade) with 160 mm crushed gravel base and 300 mm natural sandy gravel subbase layers. The subgrade soil at the test section is classified as sandy silt material with more than 25% fines content resting on bedrock layer at 3.0 to 3.5 m depth.

Pavement environmental factor data collection mainly consisted of groundwater level sensors (six groundwater rods with automatic data logger in the transverse direction of the road), subsurface volumetric moisture content sensors (four moistures rods each consisting of four sensors with automatic data logger) and temperature sensors (one frost rod). A schematic overview of the test site instrumentation is illustrated in Figure 18. The structural response of the pavement was measured using a trailer-mounted KUAB FWD device with multilevel loads.

FIGURE 17. Location of the Torpsbruk test site along county road 126 in southern Sweden.

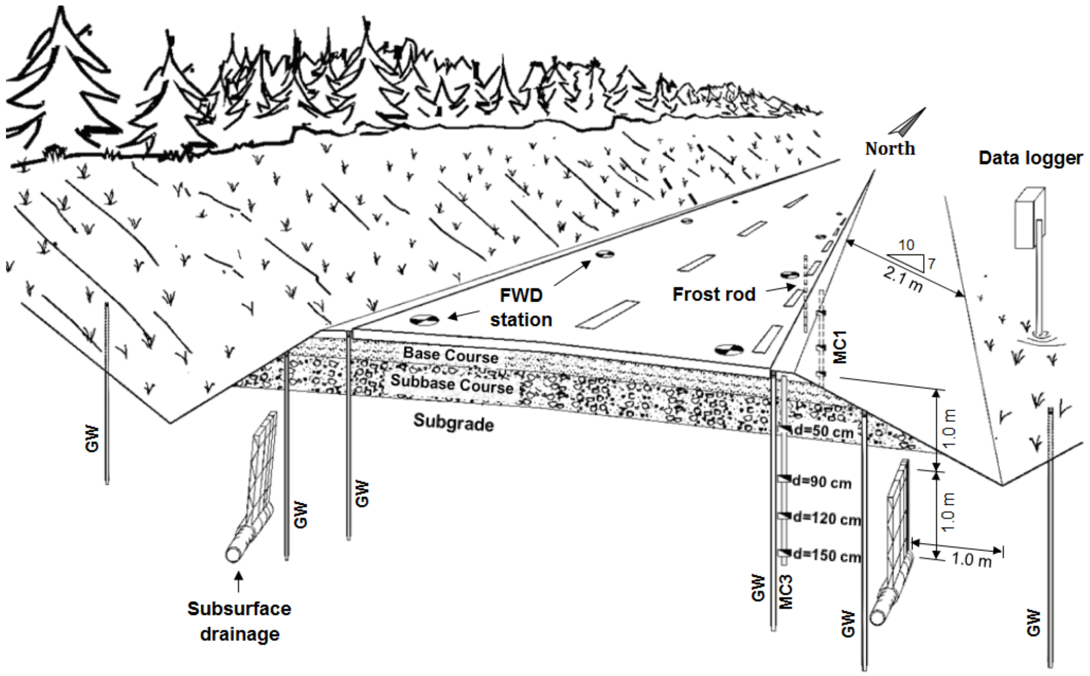

FIGURE 18. Schematic overview of the pavement instrumentations (GW: groundwater probes, MC: Moisture content probes).

Paper I mainly focuses on investigating the structural behaviour of the pavement system during the spring-thaw period in 2010 (Figure 19). During the study period, the pavement profile subsurface temperature and moisture content were measured and the structural behaviour of the pavement was assessed using frequent FWD measurements. Figure 20 shows the deflection basin variations during the thawing and the recovery periods in 2010. As thaw penetrated the pavement structure, the moisture that was accumulated in the pavement structure during the freezing period in the form of ice lenses converted back into the liquid phase. Thaw penetration broke down the particle ice-bonds which also releases excess moisture into the pavement system. This resulted in a considerable decrease in the overall stiffness of the pavement system (Figure 20, left). As the excess moisture was further drained out from the pavement structure, the unbound layers regained their pre-freezing stiffness and the pavement recovered (Figure 20, right).

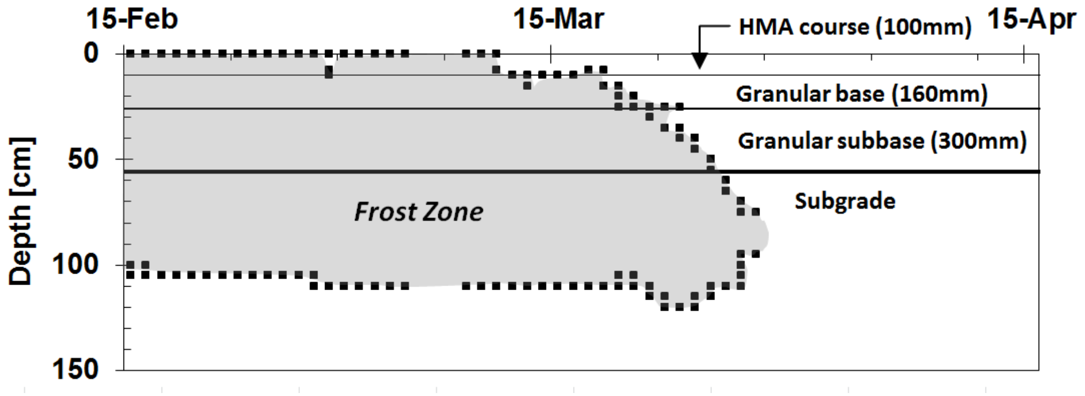

Figure 19. Illustration of frost depth and thaw penetration in the pavement structure in 2010.

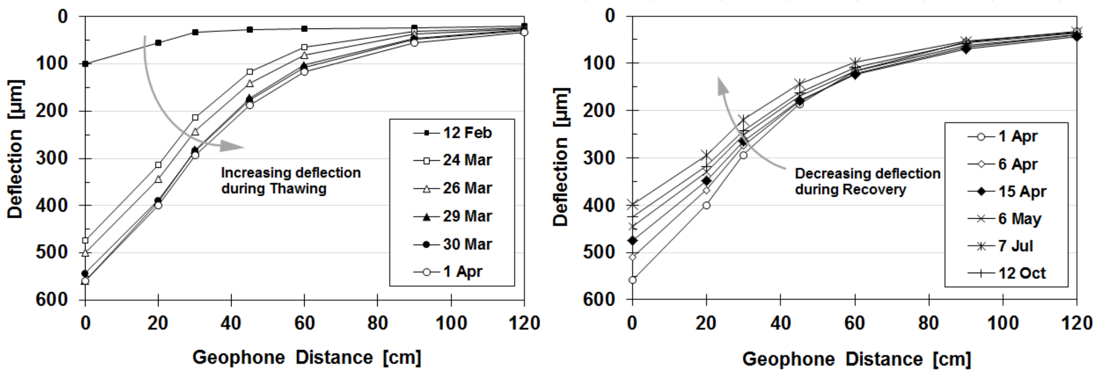

Figure 20. FWD deflection basin during thawing (Left) and recovery periods (Right) corresponding to 50 kN impact load.

The surface deflection data were later used to backcalculate the stiffness of the unbound layers with respect to thaw penetration in the pavement structure. Figure 21 represents the backcalculated layer stiffness together with the volumetric moisture measurements for the subbase granular layer and the subgrade. This figure shows the considerable effect of the moisture content on the resilient stiffness of the unbound pavement materials. Using the unbound materials in situ moduli and their respective measured moisture content, a M_R-Moisture model was presented (Figure 22). The model data fell on a unique curve and exhibited promising agreement with the predictive M_R-moisture model (given in Equation 8) that is used in MEPDG (ARA, 2004) for considering the moisture effects in unbound pavement materials.

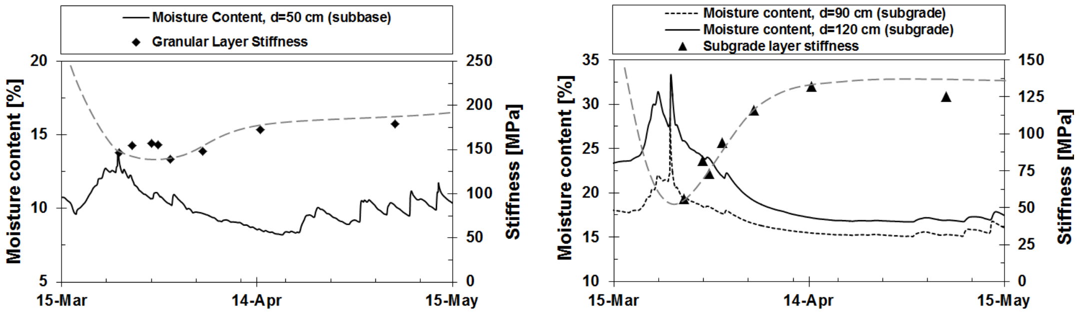

Figure 21. Backcalculated layer stiffness versus volumetric moisture content data for granular layer (left) and subgrade material (right).

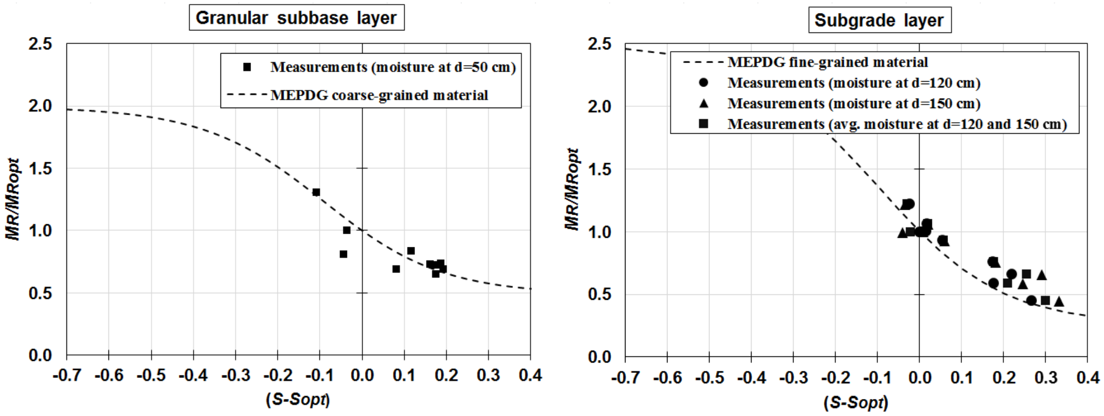

Figure 22. Backcalculated stiffness and field moisture data for granular layer (left) and subgrade material (right) versus the MEPDG predictive model.

Main findings in Paper I

- Even though the test site was equipped with a deep drainage system, considerable moisture content variation was observed in both in the granular layer and the subgrade.
- A clear correlation was observed between the thaw penetration and the measured volumetric moisture content in the unbound layers during the spring-thaw period. The highest annual moisture content in the subgrade was also measured during the spring-thaw period.
- The overall stiffness of the pavement structure was considerably affected by the spring-thaw effect. The subgrade exhibited greater sensitivity to moisture content variation during the spring-thaw compared to the unbound granular layer.
- Backcalculation of the FWD data showed evident correlation between the measured moisture content and the unbound layer and subgrade stiffness.

- During the spring-thaw, the stiffness of the subgrade was reduced by 63% while this was 48% for the granular layer.
- The backcalculated unbound layer and subgrade stiffness and their measured corresponding degree of saturation fell on a unique curve that was in agreement with the model proposed in MEPDG.

In **Paper II** the moisture content of the pavement unbound layers was deliberately changed by increasing the groundwater level through manipulation of the drainage system (Figure 23). Figure 24 represents the moisture measurement in the unbound layers during the drainage clogging and the maximum FWD deflections corresponding to a 50 kN load level.

In this study, in addition to evaluating the effect of groundwater level and unbound layer moisture content on the mechanical response of the pavement structure, the stress sensitivity of the material was also investigated. The FWD tests during this study were conducted at three different load levels (30, 50 and 65 kN). A backcalculation algorithm, illustrated in Figure 25, was proposed that could determine stiffness model parameters of the unbound materials from multilevel loads FWD test data.

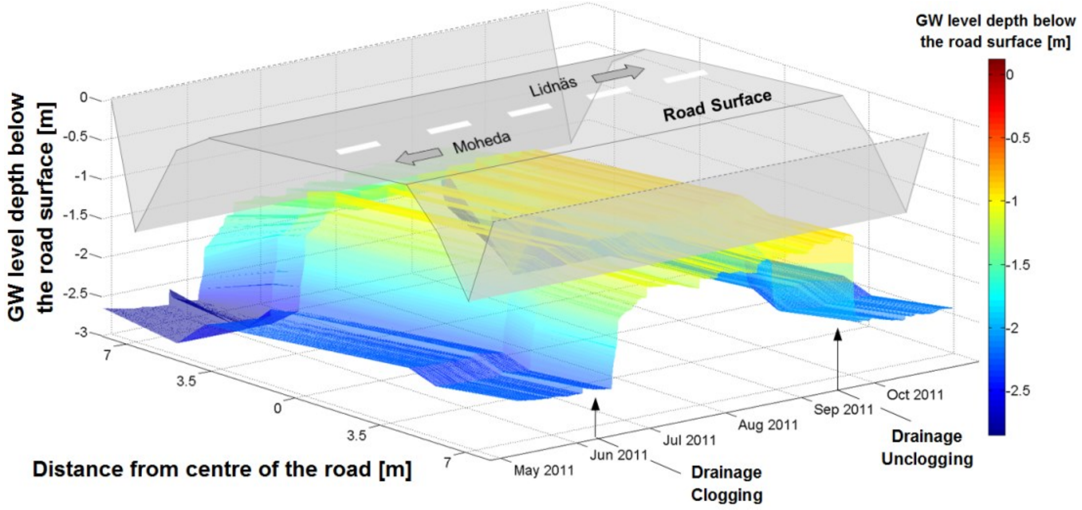

Figure 23. Groundwater level variation due to drainage clogging (registered by 6 groundwater probes across the road).

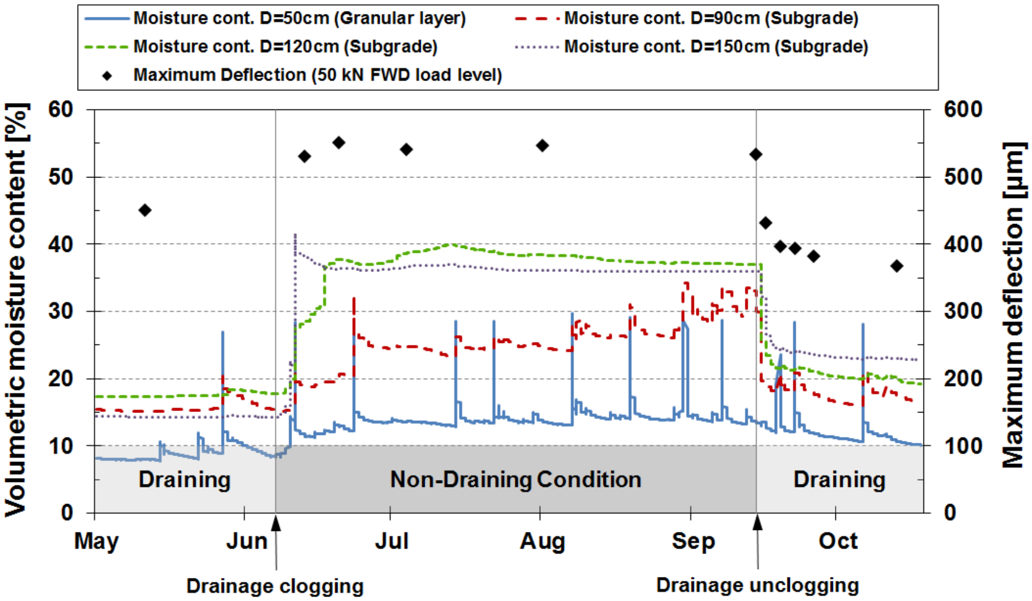

Figure 24. Subsurface volumetric moisture content variation in unbound layers due to drainage clogging and maximum 50 kN FWD deflections.

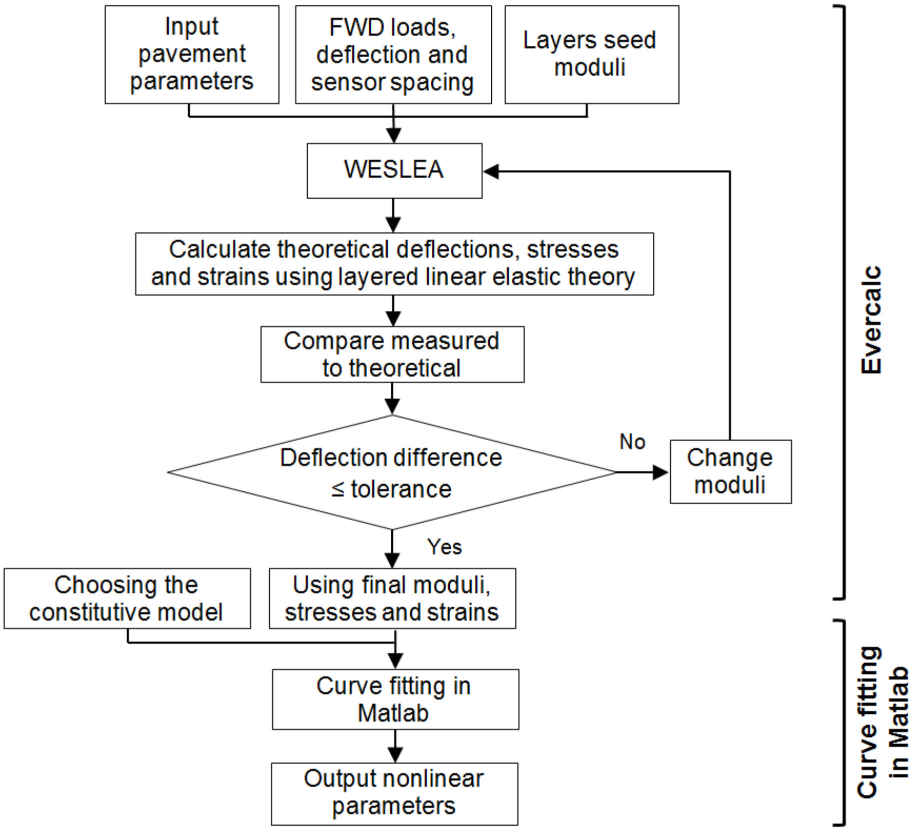

Figure 25. Backcalculation algorithm.

The moisture sensitivity and the stress dependency of the unbound materials were investigated from in situ surface deflection tests. The backcalculated granular layer and subgrade stiffness from the multilevel load deflection data and their corresponding moisture measurements are presented in Figures 26 and 27. Through the approach used in this case study the impact of moisture content on the material stiffness as well as its stress dependency could simultaneously be observed. Moisture increase in the pavement structure resulted in 38% and 37% reduction in the stiffness for the granular layer and the subgrade, respectively.

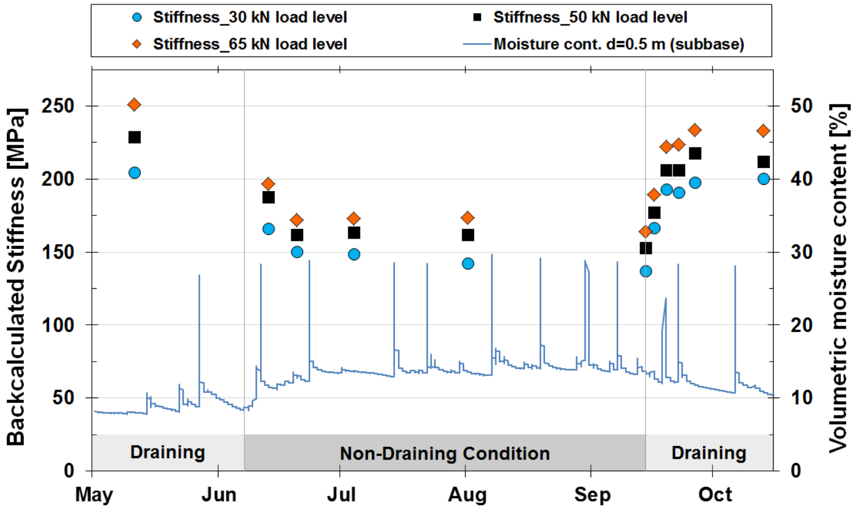

Figure 26. Layer moduli backcalculation from multilevel FWD loads for granular stiffness and their respective moisture content measurement.

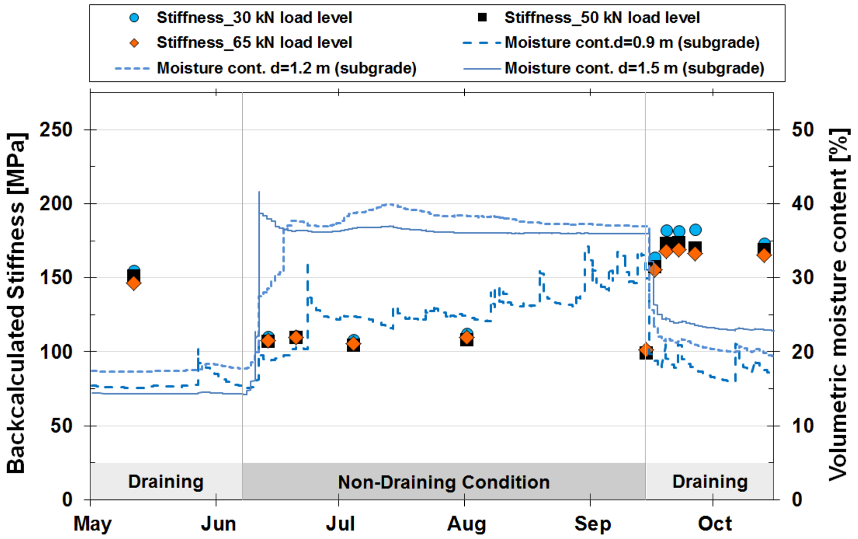

Figure 27. Layer moduli backcalculation from multilevel FWD loads for subgrade stiffness and their respective moisture content measurement.

In all the FWD performed and regardless of the moisture content, higher stiffness for the granular material was measured for increased impact load levels, demonstrating the stress hardening behaviour of the material. However, for the subgrade material the response to the multilevel loads depended on the moisture state of the material. For all the FWD measurements conducted during the draining condition in which the material was in an unsaturated state, the subgrade exhibited stress softening behaviour. Lower stiffness values were measured with an increase in the FWD load level. Similar softening behaviour is usually observed in triaxial tests in fine-grained material.

During the period in which the drainage was clogged, the subgrade was in a fully saturated condition and the backcalculated stiffness was constant regardless of the FWD load level. This can be clarified by the known behaviour of fine-grained soils in an undrained condition. In saturated undrained states, the effective confinement pressure remains constant since an increase in the confinement stress is counteracted by the pore-water pressure increase.

Main findings in Paper II

- From the summer measurements on the spring-thaw-recovered structure, it was observed that the moisture condition of the unbound layers was to a great extent dependent on the groundwater level at the pavement section. The role of the drainage system in reducing the moisture content of the unbound layers was significant.
- Similar moisture-stiffness behaviour was also observed along with manipulation of the drainage system and groundwater level.
- From backcalculation of the FWD measurements with multilevel loads, the granular layer exhibited a stress-hardening response and higher impact loads resulted in higher material stiffness.
- The silty-sand subgrade also exhibited in situ stress dependent behaviour. A stress-softening response was observed when the subgrade was in an unsaturated state. However, in saturated conditions, the subgrade showed no or negligible stress dependency and identical backcalculated stiffness was obtained regardless of the impact load level.

7.2. Paper III and IV

The effects of moisture content and suction on the resilient modulus of two silty sand subgrade soils (Luleå and Torpsbruk subgrades) were investigated using a custom-built triaxial cell that was adopted for RLT testing for unsaturated soils. The system was capable of individually controlling/measuring the pore-air and pore-pressure (and therefore matric suction, ψ_m) of the specimen during the RLT tests using high precision pressure/volume controllers (PVC) and the soil suction measuring device. Schematic diagram of the RLT test apparatus is shown in Figure 28.

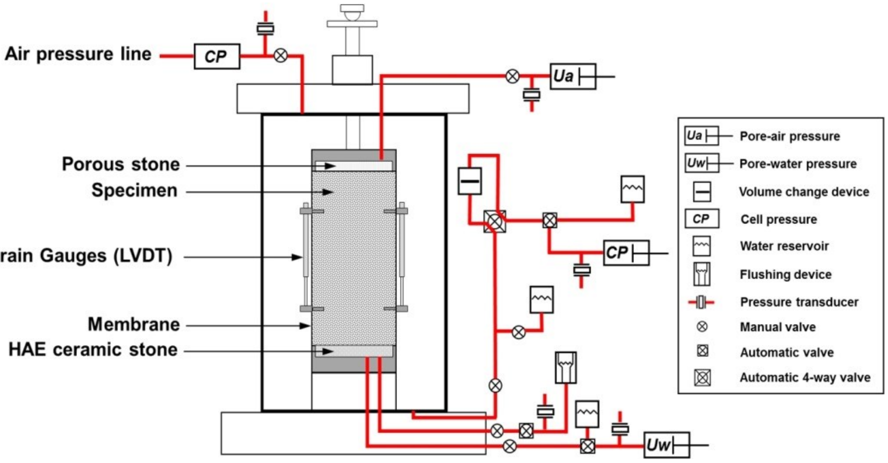

Figure 28. Schematic diagram of the suction-controlled RLT test apparatus.

For both of the subgrade soils, the resilient modulus tests were conducted at a wide range of suction (moisture content). From the RLT tests data, it was observed that the resilient modulus of subgrades were highly dependent on the net bulk stress, deviator stress and the matric suction (Figure 29).

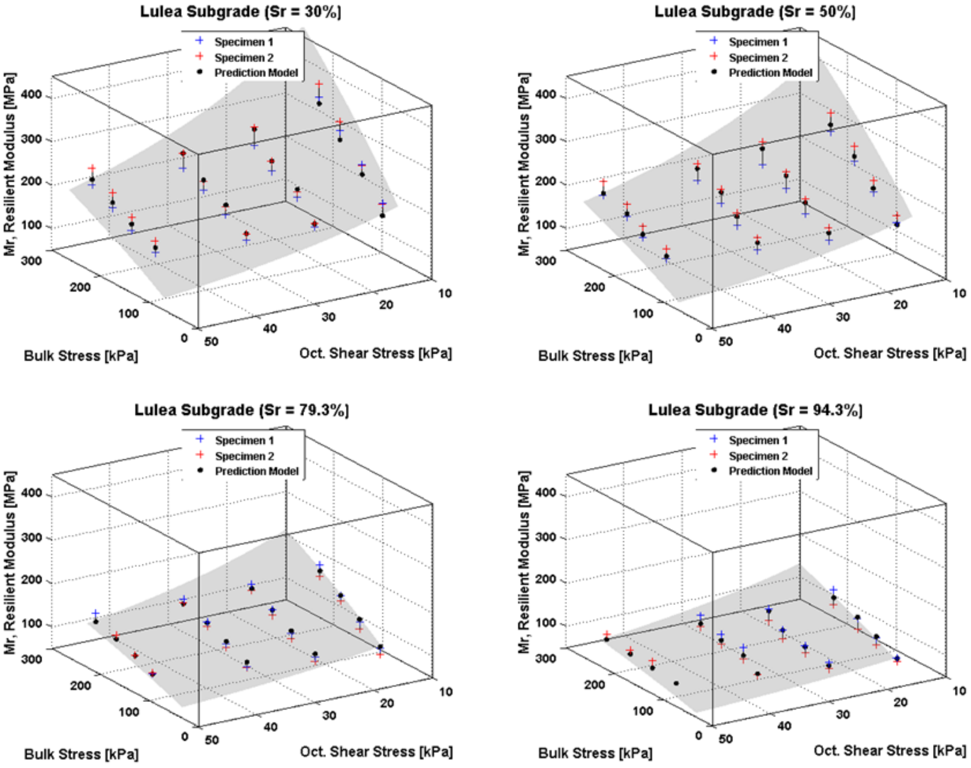

Figure 29. Resilient modulus of the Luleå subgrade soil at different suction states (degrees of saturation).

A literature survey was conducted and several recent suction-incorporated resilient modulus models were summarized (Parreira and Goncalves, 2000; Khoury and Zaman, 2004; Yang et al., 2005; Liang et al., 2008; Cary and Zapata, 2011; Nowamooz et al., 2011; Ng et al., 2013).

The dataset from the suction-controlled resilient tests were then used to calibrate several recent predictive models that account for matric suction of the soil and evaluate the capability of them in capturing the resilient response of the material under different load and moisture conditions.

Main findings in Paper III and IV

- The resilient modulus of the subgrades increased with increasing net bulk stress and decreased with increasing deviator stress (octahedral shear stress).
- Resilient modulus increased significantly with increasing matric suction.
- Change in the resilient modulus with varying net bulk and deviator stress was generally more significant at higher suction values (the degree of nonlinearity of the material stress-strain relationship was more significant at higher suction levels).
- The resilient modulus predictive models that combined the three fundamental stress state variables (net confining pressure, deviator stress and matric suction) performed more satisfactorily in capturing the resilient response of silty sand subgrade soils and their variations due to seasonal changes in the moisture content.
- Given the goodness of fit of the suction-resilient predictive models, it can be concluded that considering matric suction as an independent stress state variable in the models might be a rational approach for incorporating moisture effects in the predictive models.

7.3. Paper V

This paper spans a bridge between the field-based moisture measurements and FWD test data (Paper II) and the laboratory-based suction-controlled resilient modulus predictive model (Paper III).

The multi-level loads FWD tests that were conducted on the instrumented test section in Torpsbruk were backcalculated using the ERAPave nonlinear multilayer-elastic computer program. Depending on the subgrade moisture content measurements at different depths at the FWD test dates, the subgrade layer was divided into different sublayers in the backcalculation model and the stiffness model parameters for each sublayer were backcalculated.

Furthermore, the resilient moduli of the Torpsbruk subgrade sublayers at their corresponding measured moisture contents (suctions) on the FWD dates were calculated using the laboratory-based suction-resilient model developed in Paper III. The backcalculated subgrade stiffness obtained for all of the FWD test dates and load levels were compared with the resilient modulus results obtained from the laboratory-based suction-resilient modulus model (Figure 30).

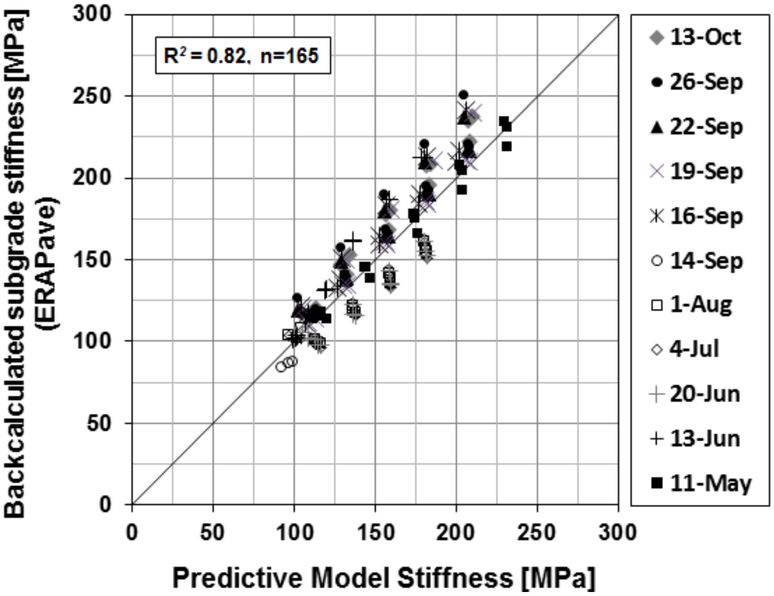

Figure 30. Laboratory-based resilient modulus versus backcalculated moduli using nonlinear model in ERAPave.

Both the field measurements and the laboratory tests confirmed the stress and moisture dependence of the subgrade material modulus. In general, good agreement was observed between the in situ backcalculated stiffness and the suction-model based moduli.

Main findings in Paper V

- The subgrade sublayers degree of saturation varied between ~ 45 to ~100% during the field FWD tests. For this range of variation, the matric suction accounted for about 30% of the subgrade resilient modulus variation.
- The enhanced predictive suction-resilient modulus model in Paper III seemed to satisfactorily capture the moisture content variation effects on the resilient modulus.
- In general, the subgrade moduli calculated by the enhanced predictive suction-resilient modulus model and the backcalculated stiffness obtained from the FWD field data showed good agreement, concluding that the modulus-suction model could efficiently capture the seasonal variation effects.

7.4. Paper VI

Rutting is one of the main distress modes in flexible pavements. In thin pavement structures, rutting is often associated with accumulation of permanent deformation in unbound layers under repeated loads. Realistic prediction of surface rutting requires models that can reliably capture the cumulative plastic deformation of pavement unbound layers under repetitive traffic loads. Paper VI presents an evaluation of several models that incorporate the time-hardening concept for prediction of permanent deformation of unbound materials using data from tests conducted on two different silty sand subgrade materials.

The time-hardening concept was adopted on the Tseng and Lytton (1989), Gidel et al. (2001) and the Korkiala-Tanttu (2005) permanent deformation models so that the data from the multistage RLT tests could be used for the evaluation. These permanent deformation models combine the influence of the number of load applications with the effect of material stress state. The details of these modified models are presented below.

The modified Tseng and Lytton (1989) model assumes a direct relationship between the permanent strain and the resilient strain and is presented as follows:

$$\hat{\varepsilon}_{p_i}(N)=\varepsilon_{r_i}\varepsilon_0 e^{-\left(\frac{\rho}{N-N_{i-1}+N_i^{eq}}\right)^{\beta}} \qquad [9]$$

where, $\hat{\varepsilon}_{p_i}$ is the accumulated permanent deformation and ε_{r_i} is the resilient strain in the stress path i. The ε_0, ρ and β are material parameters and N_i^{eq} is defined as follows:

$$N_i^{eq}=\rho\left(-\ln\left(\frac{\hat{\varepsilon}_{p_{i-1}}}{\varepsilon_{r_i}\varepsilon_o}\right)\right)^{-1/\beta} \qquad [10]$$

The modified Gidel et al. (2001) model additionally requires shear strength parameters (obtained from static triaxial tests) and is rewritten as followed:

$$\hat{\varepsilon}_{p_i}(N)=\varepsilon^0\left(1-\left(\frac{N-N_{i-1}+N_i^{eq}}{100}\right)^{-B}\right)\left(\frac{L_{\max,i}}{p_a}\right)^{u}\left(m+\frac{s}{p_{\max,i}}-\frac{q_{\max,i}}{p_{\max,i}}\right)^{-1} \qquad [11]$$

where ε^0, B and u are material parameters. $p_{\max}$ and $q_{\max}$ are the maximum applied hydrostatic stress and deviator stress, respectively, and $L_{\max,i}=\sqrt{p_{\max}+q_{\max}}$. The parameters m and s are the slope and the intercept of the Mohr-Coulomb failure line in the $p-q$ space, respectively, obtained from static triaxial tests. p_a is the reference stress, here selected as100 kPa.

$$N_i^{eq} = 100\left(1 - \frac{\hat{\varepsilon}_{p_{i-1}}}{\varepsilon^0}\left(\frac{L_{\max,i}}{p_a}\right)^{-u}\left(m + \frac{s}{p_{\max,i}} - \frac{q_{\max,i}}{p_{\max,i}}\right)^{-1}\right)^{-\frac{1}{B}} \quad [12]$$

The modified Korkiala-Tanttu (2005) model for multistage test procedure is presented as follows:

$$\hat{\varepsilon}_{p_i}(N) = C(N - N_{i-1} + N_i^{eq})^b \frac{R_i}{A - R_i} \quad [13]$$

$$N_i^{eq} = \left(\frac{\hat{\varepsilon}_{p_{i-1}}(A - R_i)}{CR_i}\right)^{\frac{1}{b}} \quad [14]$$

where C is material parameter and R_i is the shear stress ratio of the deviator stress in the stress path i to the deviator stress at failure. A is the maximum theoretical value for the shear stress ratio and parameter b is recommended as follows (Korkiala-Tanttu, 2005):

$$b = cR + d \quad [15]$$

where c and d are material parameters.

In all of the equations above, the subscript i refers to the i^{th} stress path. The multistage repeated load triaxial (RLT) tests were carried out on two silty sand subgrades at four different moisture contents.

The test data were then used to optimize the material parameters for each predictive model and moisture content. The calibrated model curves and the measured data together with the shakedown ranges are presented in Figures 31 and 32.

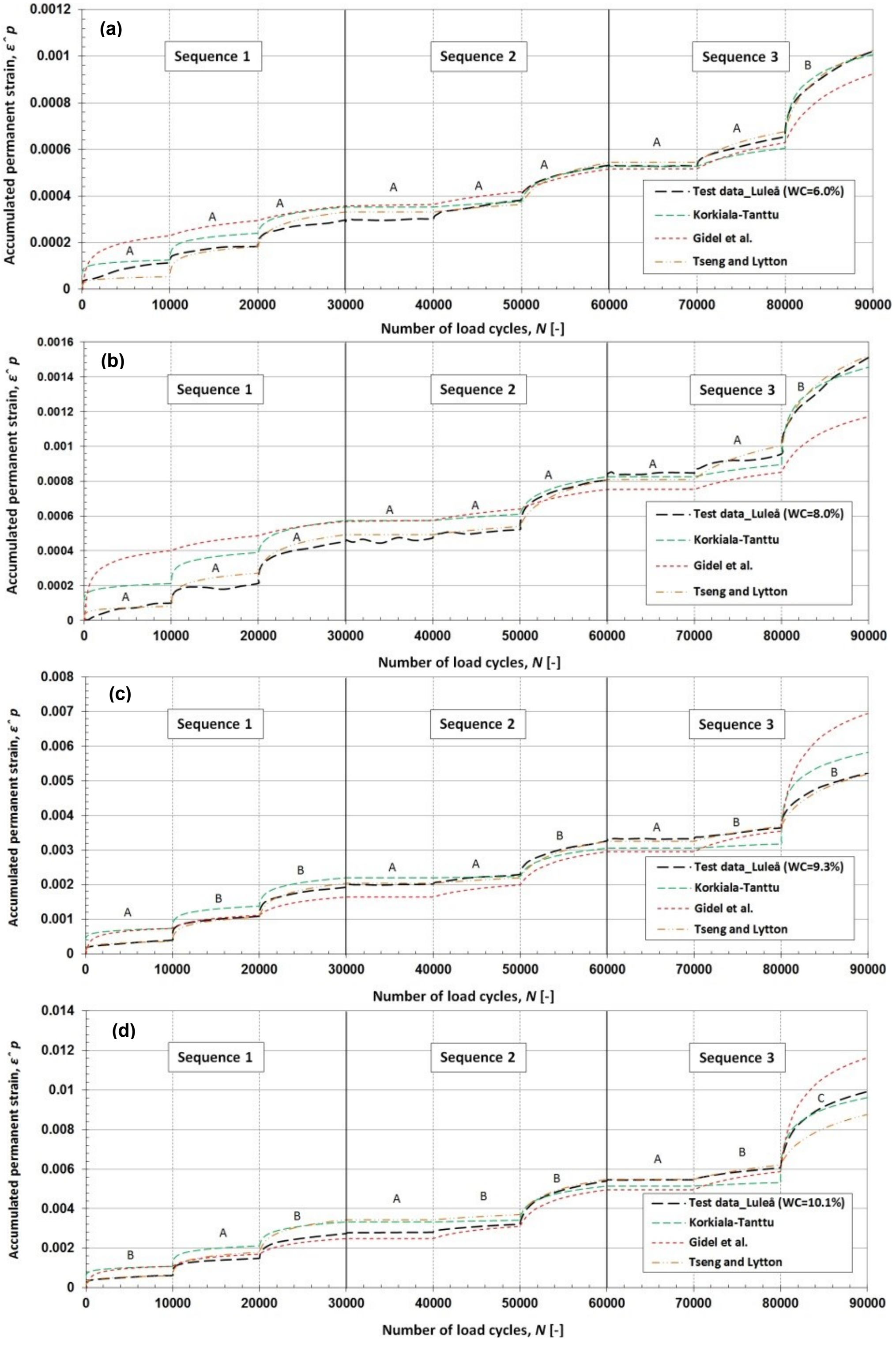

Figure 31. Accumulated permanent deformation from RLT tests and calibrated models for Luleå subgrade at moisture content: (a): 6.0%; (b): 8.0%; (c): 9.3%; (d): 10.1%.

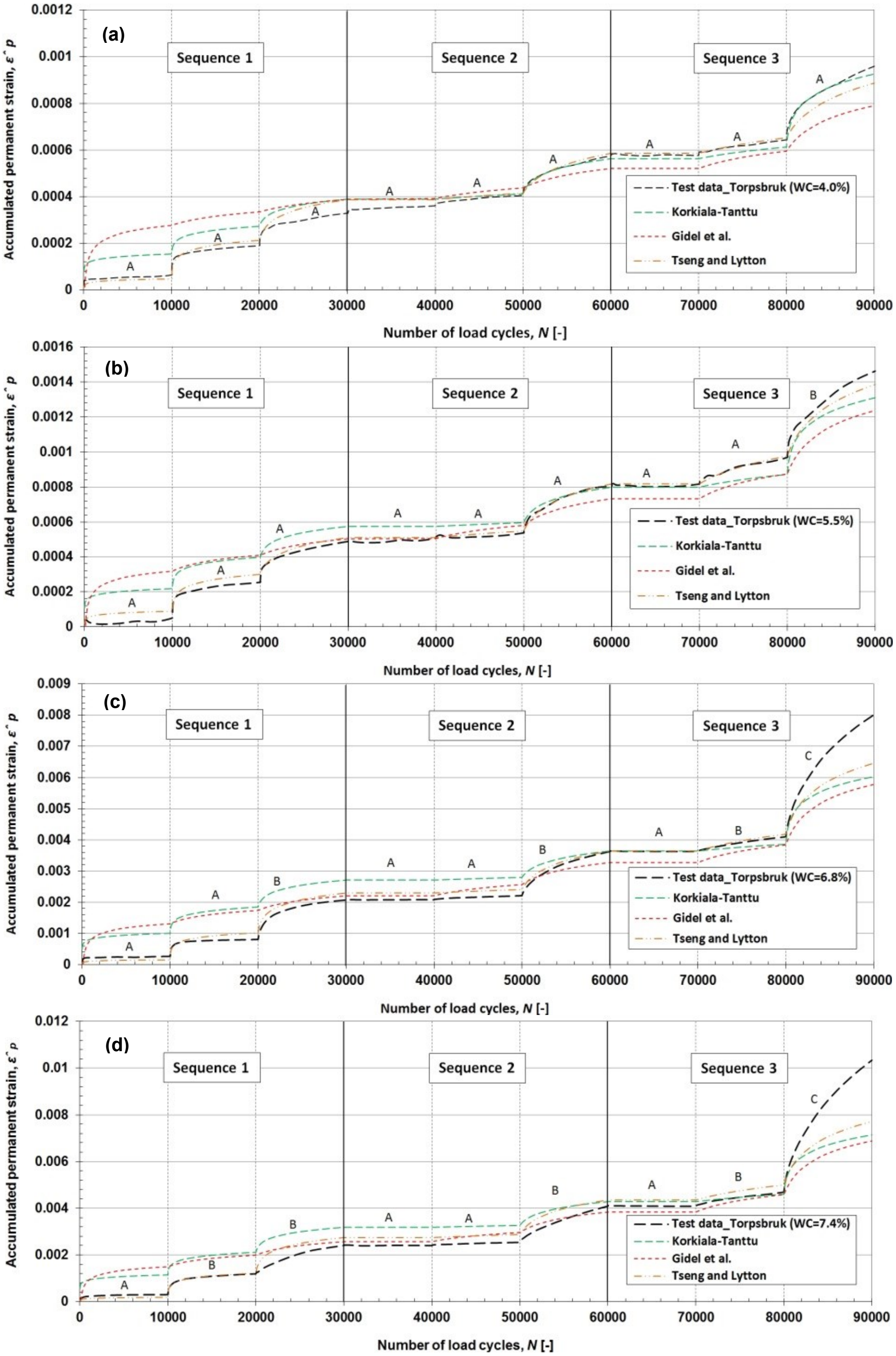

Figure 32. Accumulated permanent deformation from RLT tests and calibrated models for Torpsbruk subgrade at moisture content: (a): 4.0%; (b): 5.5%; (c): 6.8%; (d): 7.4%.

Main findings in Paper VI

- Generally, it was observed that the modified models that are based on the shakedown approach performed reasonably well in capturing the permanent deformation behaviour of the selected silty sand subgrade soils using data obtained from the RLT tests.
- Minor discrepancies between the predictive models were observed confirming the potential of using RLT test data and the presented approach for characterizing the permanent deformation of subgrade soils.
- Among the models used, the Tseng and Lytton (1989) model exhibited the best performance in most of the cases (different moisture content), considering the goodness of fit of the model and the accuracy in predicting the shakedown ranges at different stress paths.
- In most of the cases in the studied models, it was observed that usually several combinations of parameters would provide acceptable fit to the test data. The inconsistency in the acceptable range for the parameters was also observed in the literature, implying the apparent need for conducting more permanent deformation tests in order to set up a widely accepted range limits for the parameters of different models and/or possibly develop simpler models with a minimum number of parameters and validating these models through full-scale experiments on pavement structures.

8. Summary and Conclusions

In cold regions, climatic factors can significantly affect the mechanical behaviour of unbound materials which can influence the overall performance of a pavement. Climate-related pavement deterioration imposes considerable maintenance and rehabilitation efforts on road authorities as well as on public expenditure. In pavement unbound materials, moisture content and temperature (sub-zero temperature) are the two main climatic parameters influencing the mechanical behaviour of unbound layers. Environmental factors, their interaction with pavements and their influence on material behaviour are highly complex in nature. Despite the considerable number of studies that have been conducted during past years, fundamental understating of material behaviour and modelling with respect to environmental factor effects is still lacking.

Many studies on stress and moisture dependency of unbound materials are conducted through laboratory experiments which may not fully represent the field conditions. The research work presented in the first part of this thesis intended to provide more insight into pavement in situ environmental factors, unbound material stiffness behaviour and their interaction through field studies. For the field investigation, the Torpsbruk test site was instrumented with moisture, temperature and groundwater level probes and the mechanical behaviour of the pavement was assessed using an FWD device with multilevel impact loads. The pavement environment and structural behaviour were assessed during a spring-thaw period as well as a case study in which the groundwater level at the test site was changed by manipulating the drainage system.

The second part of this thesis was mainly based on laboratory investigations through RLT tests using a modified triaxial chamber that allowed for pore suctions measurements throughout the test. The laboratory investigation of moisture effects on pavement unbound materials were based on developing an enhanced approach in predicting the stiffness of the material using principles of soil mechanics for partially saturated conditions and incorporating soil suction in the resilient modulus constitutive models.

The permanent deformation properties of the subgrade materials and their sensitivity to moisture content variation have been less studied despite their importance in formation of rut depths in thin flexible pavements. The study conducted here showed the feasibility of using the multistage RLT test for evaluating the permanent deformation properties of fine-grained subgrades. Furthermore, predictive models that were based on multistage RLT tests and the time-hardening approach were developed. This can significantly reduce the time and effort required for conducting permanent deformation tests.

The work summarized in this thesis covers different aspects of moisture effects on pavement unbound materials, using both field and laboratory studies. The main findings from each individual study are given in the summary of the respective appended papers. In brief, some of the major finding of the studies can be summarized as the following.

From both the field measurements (spring-thaw and groundwater level variations) and the laboratory-based studies it was observed that the moisture content has a significant effect on the mechanical response of the unbound materials and subgrade. In general, as moisture content increased, the stiffness of unbound materials and their resistance to withstand accumulation of permanent deformation decreased. The field measurements at the instrumented test section in Torpsbruk indicated the feasibility and potential of using in situ measurements to better understand the seasonal environmental effects on pavement performance. Even though field studies and instrumentation can be quite challenging and costly, the outcome of these studies can be very valuable and of great interest for developing response models (i.e. moisture-stiffness models). Field measurements can provide in-depth information about the stress and moisture dependency of the material that is so far mainly studied in the laboratory and may not fully represent in situ conditions.

Concerning seasonal variation in the resilient modulus due to moisture changes, it was observed from the laboratory study (using RLT tests on two silty sand subgrades) that matric suction could be used and incorporated into the prediction models. Matric suction is the state variable with highest relevance to unsaturated soil mechanics and is highly dependent on the soil structure moisture content. Since moisture content is the main environmentally driven factor affecting the behaviour of unbound layers with a high fines content and subgrade soils, matric suction can be incorporated into the resilient modulus models.

Regarding the permanent deformation study, the multistage RLT tests and modelling procedure based on the time-hardening approach were selected. This allowed for more comprehensive study of the material stress dependency compared to the conventional single stage RLT procedures. The multistage RLT test procedure enabled testing the material under a wider range of stresses with considerably less laboratory effort and time. This study also showed the significance of moisture content on the permanent deformation behaviour of the two different silty sand subgrade materials that were tested.

8.1. Assumptions and limitations

The environmental data collected during the study period were limited to certain locations throughout the test section. However, the temperature and moisture profile measurements were assumed to be identical throughout the whole test section. A similar assumption was made for the deflection measurements. Since the pavement structure at the test road section was in-service, a number of the FWD measurements were limited due to traffic safety regulations. This study was to a considerable extent based on data collected by in situ measuring instruments and their accuracy level. The findings from this study are limited to findings from a certain pavement structure and test site and therefore cannot be generalized. It would be beneficial to compare the test results from this study to results from other pavement structures and test sites. For the laboratory-based investigations, it is believed that incorporating soil suction into predictive resilient modulus models appears to give a new insight into predicting seasonal resilient modulus variation due to moisture content changes. However, further validation across a wider range of materials may be required, for both the approach and the recommended parameters.

8.2. Recommendations for future work

From the research carried out in this thesis, there are still many questions that need to be further investigated in future research studies. The field study carried out here was limited to a single specific test site with specific properties. The response and the stress dependency of the unbound layers and their correlation to the measured moisture content were evaluated using backcalculation of the surface deflection data. Direct measurement of in situ stresses and strains using pressure and deformation gauges along with moisture sensors (or even suction measurement sensors) under moving traffic loads and their response to seasonal moisture variation would be an interesting question, which should be further investigated.

Considering the importance of permanent deformation in unbound pavement layers in rut formation, particularly in thin flexible pavements, it is evident that more studies need to be carried out on the permanent deformation properties of unbound materials and the influence of the moisture content. Even though only two subgrade soils were tested, it was observed that in most of the current permanent deformation models (due to multiplicity of the model parameters) usually several combinations of parameters would provide acceptable fit to the test data. This can cause a major confusion for a user to select the right set of parameters when trying to predict the permanent deformation of the material in question. This major drawback is probably due to lack of sufficient permanent deformation studies There is an apparent need and is recommended that more permanent deformation tests be conducted to set up widely accepted range limits for the parameters of different models and if possible develop simpler models with a minimum number of parameters.

Moreover, more research needs to be carried out to calibrate and implement permanent deformation models that are based on data from multistage RLT tests. Comparing the laboratory-based model predictions against the in situ pavement data or controlled APT tests would be recommended as part of the evaluation and validation of the models.

Finally, and as the field and laboratory measurements illustrated, the environmental factors and their effect on pavement material behaviour and performance are very complex in nature and it is believed that more research studies are certainly required to progressively obtain a more complete understanding of the phenomena involved through both laboratory and field measurements. This will assist in developing mechanistic approaches that can quantitatively account for climatic factor effects on material behaviour and pavement performance.

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