Falling Weight Deflectometer Interpretation of Pavement Behaviour during Spring Thaw

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ABSTRACT

A rural county road consisting of a thin flexible pavement structure in southern Sweden was instrumented in year 2009 in order to monitor changes in pavement characteristics caused by seasonal variations in environmental factors. Subsurface pavement temperatures, moisture phase and moisture contents were constantly measured throughout the study with main focus on the spring thaw and recovery periods. The pavement structural response was surveyed by conducting Falling Weight Deflectometer (FWD) measurements during these periods. Changes in pavement layers moduli were estimated by performing backcalculations on the deflection data using the Evercalc computer program. Furthermore, deflection basin indices were analysed using the FWD data.

Pavement stiffness decreased significantly when the base and the subgrade began to thaw. Changes in backcalculated layers moduli showed clear correlation with layers moisture content measurements. The field data showed a considerable decrease in the bearing capacity of the pavement structure when the highest annual moisture in subgrade was also registered. Both deflection basin indices and backcalculated layers moduli indicated that the pavement was weakest when the subgrade completely thawed. Thereafter, the pavement gradually regained its stiffness as the excess water drained out from the layers. Complete recovery of the pavement took more than one month. Backcalculations of the FWD data showed 63 percent loss in the subgrade modulus and 48 percent loss in granular base and subbase moduli respectively during spring thaw compared to the summer values.

KEY WORDS: Falling Weight Deflectometer (FWD), backcalculation, thaw weakening, bearing capacity, moisture.

1 BACKGROUND

The road network represents a large part of a national infrastructure and is a key element in the domestic and global commerce for all countries. Construction, operation and maintenance of the road network consume a considerable part of the national annual budget. A sustainable transportation infrastructure that can assure an all-season performance requires a comprehensive asset management system. Understanding the pavement structural behaviour and developing realistic models enhances approaching a robust asset management system. Adequate prediction and simulation of pavement material properties that take account of year-around variations are primary conditions for developing such models.

Pavement moduli variations due to seasonal changes in environmental factors are common in cold regions. The most significant pavement moduli variation occurs when pavement freezes, thaws and subsequently recovers. These changes are rather complex and vary depending on the geographical position, meteorological conditions and pavement structures. The principal change in the overall stiffness of freezing pavements is illustrated in Figure 1. A considerable part of the road network in Nordic countries experience freezing during the winter and thawing in the beginning of the spring. The penetration of the frost in winter increases the overall stiffness of the pavement structure. The formation of the frost zone varies depending on the duration and intensity of the freezing temperatures. In general, low temperatures decrease the viscosity of the asphalt layer (Huang, 2003). Moreover, in pavement unbound materials, frost penetration produces strong ice bonding between the particles resulting in considerable increase in the resilient moduli (Simonsen and Isacsson, 2001). As a result, the frozen pavement can withstand heavy loads without any considerable structural damage.

During the spring, the accumulated frozen water in unbound layers thaws. The thaw initiates at the top of the pavement and progresses rapidly in the granular base and subbase layers. The released water in granular layers can be temporarily trapped by the underlying frozen layer and causing a near-saturation condition in these layers. This moisture increase can considerably reduce the bearing capacity of the unbound layers. Poor support from the underlying granular layers during this condition may result in accelerated fatigue damage in the bound layer (Doré and Zubeck, 2008). The thaw will further progresses in the subgrade soil resulting in prospective water saturation and possible build-up of pore-water pressure. High pore-water pressure changes the effective stress state and reduces the shear strength (Simonsen and Isacsson, 1999). Significant decreases in resilient moduli of subgrade soils when the excess-water during thawing releases have been reported. Simonsen and Isacsson (1999) investigated the resilient behaviour of three subgrade soils during freezing and thawing using constant and variable confining pressure triaxial testing. The study showed significant reduction in resilient modulus after freeze-thaw utilizing both methods. Erlingsson (2010a) showed through an accelerated pavement testing using Heavy Vehicle Simulator (HVS) in Sweden that, both the resilient and the permanent strains in unbound layers increased when the ground water table was raised in the pavement structure. This reduced the resilient modulus of the unbound layers. The increase in resilient and permanent strains of unbound layers can result in accelerated pavement damage.

Several investigators have claimed spring thaw to be the most significant deterioration factor for these pavements (White and Core, 1990; Janoo and Berg, 1990). In pavements subjected to freezing, the relative load-induced damage during spring thaw could be 1.5 to 3 times higher than the average annual damage (St-Laurent and Roy, 1995). A common practice to protect pavement structures from excessive damage during this period is to apply load restrictions on trucking industries until the pavement gains back its pre-freezing strength. However, due to the variability of the environmental conditions and the complexity of the phenomena, it is difficult to determine when these restrictions should be set and removed.

When the subgrade completely thaws, the excess pore-water gradually drains out from the pavement structure. The pavement layers usually gain back their prefreezing strengths. This period is known as the recovery period. The length of the recovery period can vary from several weeks to several months, depending on the pavement and the surrounding conditions. In granular base and subbase layers, the stiffness regains shortly after the thaw is over. However, in subgrade soils with high fine content this period is normally longer (Charlier et al., 2009).

2 STUDY OBJECTIVES

The overall objective of this study was to investigate the structural behaviour of a flexible pavement subjected to freezing temperatures in southern Sweden. Major attention was paid to pavement subsurface temperature, moisture content and phase changes during freezing, thawing and recovering periods. This study describes some of the field data that were obtained, the changes in moduli of the granular layer and subgrade that were perceived, and their relationships to moisture content during these periods. It was anticipated that this study could call further attention and set the stage for further field and laboratory-based research work addressing the critical spring-thaw period.

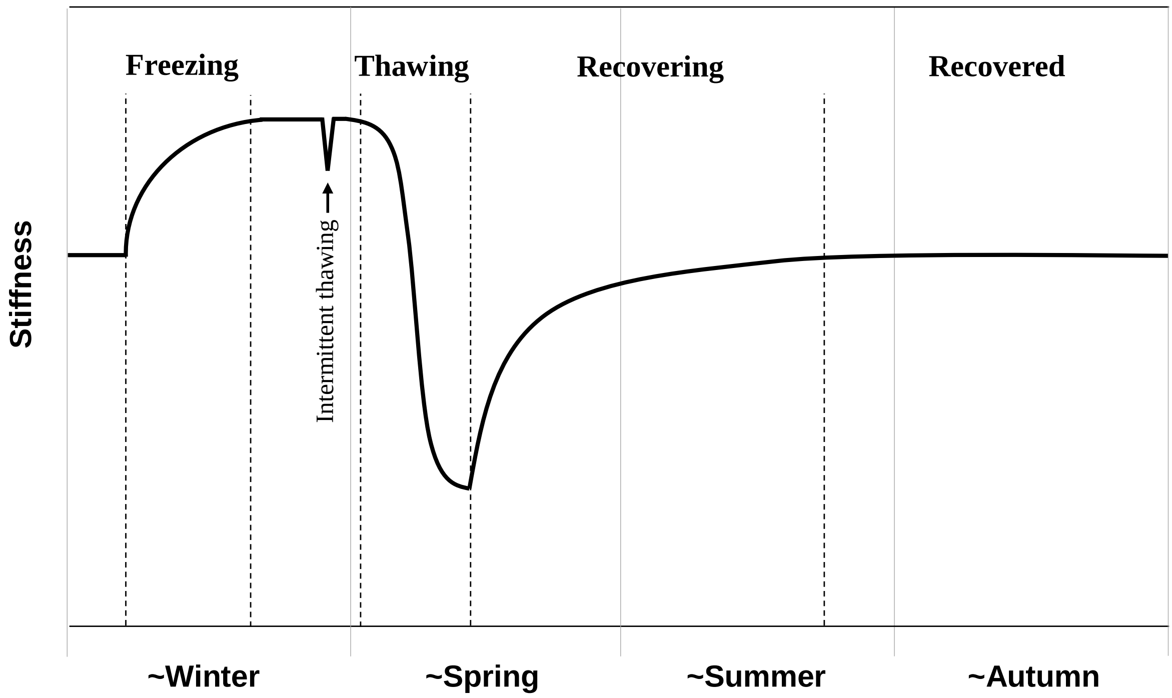

Figure 1: Conceptual pavement stiffness variations due to freezing and thawing.

3 FIELD OVERVIEW

The study presented here was performed based on measurements from the instrumented section on Lv126 county road at Torpsbruk. The Lv126 is a two-lane two-directional rural road in the province of Småland, in southern Sweden. It is a typical three layer flexible pavement structure with relatively low traffic volume. The data collected at this test section included subsurface temperatures, moisture content and moisture phase, groundwater level and surface deflections. The test site was located in southern part of Sweden as shown in Figure 2.

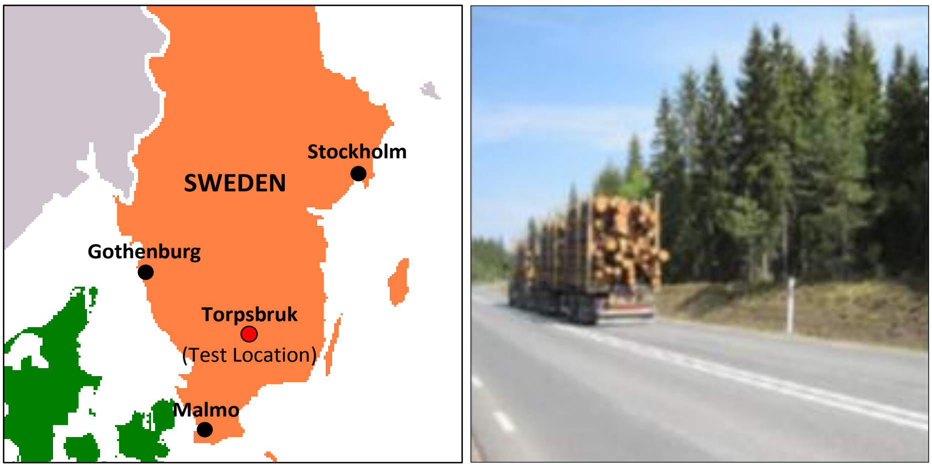

Figure 2: Location of Torpsbruk test site in province of Småland in Sweden (Left), Overview of the Lv126 county road (Right), (Geographical coordinates: 57.047600, 14.566020).

3.1 Pavement structure

The pavement structure at the test section consisted of 100 mm Hot Mix Asphalt course, 160 mm crushed gravel base and 300 mm natural sandy gravel subbase resting on a sandy silt subgrade. The HMA layer was a dense graded mix with 16 mm maximum grain size. Bituminous binder (pen 160/220) was used in the mix.

3.2 Subsurface temperature and moisture measurements

The pavement subsurface temperatures were measured using the Tjäl2004 frost rod. It consisted of a series of temperature sensors along a metal rod placed in a casing. Temperature sensors registered data at every 5 cm interval down to the depth of 2 m. The sensors were calibrated to give the highest accuracy close to 0°C, where the freezing starts, and had an accuracy of ± 0.05°C. Readings were registered wirelessly by an automatic data logger at 4 hours intervals (Charlier et al., 2009).

Subsurface moisture contents were registered using four EnviroSMART™ moisture probes. Three of the moisture probes were installed along the unpaved shoulder of the road and one was mounted in the pavement verge. Measurements from two of the moisture probes that showed robust values were used throughout the study period. Each moisture probe consisted of four sensors. One of the sensors was placed close to the bottom of the subbase layer (at 50 cm depth) and three others were placed in the subgrade (at 90, 120 and 150 cm depths respectively). An automatic data logger registered moisture measurements at 30 minutes intervals. The probes were high-frequency capacitance probes which determined the volumetric moisture content through dielectric constant measurement. The dielectric constant of the soil is highly dependent on its liquid pore-water. Dry soils have values of dielectric constant of 2 to 6. The dielectric constant of liquid water is between 79 and 82 while it is around 3 for solid water (Erlingsson et al., 2009). Therefore, sharp decrease (or increase) in moisture measurements correspond to the freezing or thawing of the soil pore-water. A detailed description for the instrumentation was done by Salour and Erlingsson (2012).

The frost and thaw depths in the pavement can be determined reliably using both the subsurface temperature and the dielectric constant (Jong et al., 1998). In this study, frost depths were determined using the data from the Tjäl2004 frost rod. Frost and thaw depths during year 2010 winter and early spring are shown in Figure 3. Maximum frost penetration of 1.2 m was observed during this period. Top-down, bottom-up thawing began before mid-March and the pavement fully thawed by April.

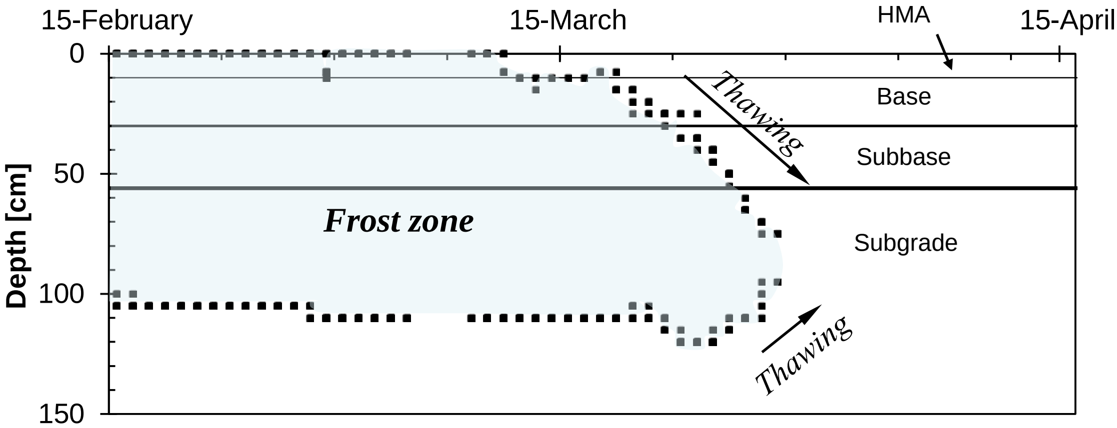

Figure 3: Depth of frost and thaw at Torpsbruk site during 2010.

4 FROST-THAW AND MOISTURE CONTENT

Figure 4 illustrates the pavement subsurface temperature and volumetric moisture variations during the thaw progression and the recovery period. It can be seen in Figure 4 that from 26th of February to 1st of March, the temperature at the bottom of the HMA layer rose to positive values with a peak value of 3.6ºC on the 28th of February. Consequently, the moisture increased in subbase (d= 50 cm) and upper subgrade layer (d= 90 cm) during this period. The increase was quite considerable in the upper subgrade compared to the subbase layer. The volumetric moisture content in the upper part of the subgrade increased from 18.4 percent to 36.2 percent, nearly a twofold rise. This could be explained to be the result of the liquefied water draindown from the upper layers as well as the attraction of pore-water from adjacent voids. The liquid water may have been trapped in the upper unfrozen part of the subgrade during this period, since no effective drainage path did exist. This hypothesis was supported since the temperature at lower subgrade level (d=120 cm) remained below freezing temperatures during this period explaining the constant trend in moisture in the lower subgrade levels as the water still remained in frozen state. The increase in moisture was from 14.6 percent to 22.3 percent at 120 cm depth and almost insignificant at 150 cm depth in the subgrade. In the subbase layer, moisture only increased from 11.8 percent to 15.4 percent. Unlike the subgrade, the base and subbase layers showed high fluctuations in moisture content during the short intermittent winter thaw periods.

On the 1st of March, the temperature at the bottom of the HMA layer dropped to sub-zero values for a period of ten days. This resulted in re-freezing of the subbase layer and upper subgrade. A considerable decrease in moisture was seen in the subbase layer, from 15.6 percent on the 1st of March to 7.8 percent on the 9th of March.

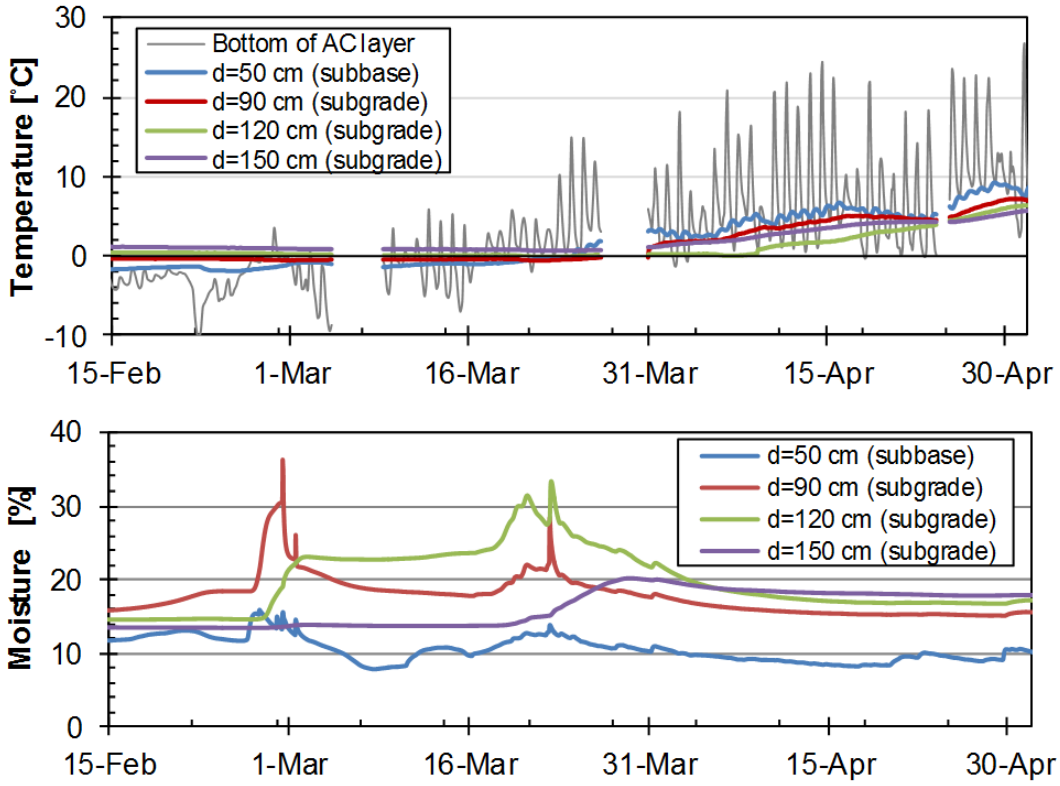

Figure 4: Pavement environmental data during thawing and recovering, 2010. Subsurface temperatures (Top) and subsurface volumetric moisture content (Bottom). (Gap in the temperature data set is due to lack of battery supply).

The major spring thaw in unbound layers started before mid-March when the mean temperature at the bottom of the HMA layer as well as the subbase and subgrade levels gradually rose to positive values. In a period of more than two weeks, the frozen pavement structure fully thawed (Figure 3). During this period, all moisture probes showed a significant rise with the uppermost sensors being first to respond. The peak moisture value for the subgrade during this period was 33.5 percent at the depth of 120 cm on the 23rd of March. The lower subgrade levels experienced considerable increase in moisture content when the thawing progression reached the subgrade. After reaching a peak on the 23rd of March in the subbase layer and the upper subgrade, the moisture started to decrease at a slow rate due to the drainage of excess water. A similar trend was observed in all of the probes. This period is known as the recovery period.

In the subbase layer, the excess moisture drained out in less than two weeks while it took nearly one month for the subgrade layer (Figure 4, bottom). Minor fluctuations in moisture during the first two weeks of April, particularly in the upper layers were related to the few freezing days during this period. Figure 4 shows that the moisture in the granular layer was considerably lower than the moisture content in the subgrade material which is due to lower fine content in the granular layers compared to the subgrade and as a result higher permeability. Assuming that the moisture content in unbound layers governs its stiffness, granular materials were less affected by frost and thawing action. For the same reason, the granular layer also showed a shorter recovery period compared to the subgrade.

5 PAVEMENT STIFFNESS

5.1 Deflections

Pavement surface deflections were measured using Falling Weight Deflectometer (FWD). KUAB 50 equipment was used for the deflection measurements. The KUAB FWD is a trailer-mounted device and produces a haversine impulse load using a double-mass and buffer system. Deflections were measured along the outer wheel path of the road. A series of 50 kN impact-loads were applied through a 300-mm-diameter plate. Surface deflections were measured at distances of 0, 200, 300, 450, 600, 900, and 1200 mm from the centre of the loading plate. Deflection measurements were taken with an attempt to capture the thawing and the recovering. Each set of FWD tests consisted of 23 stations at one metre intervals. The FWD measurements were attained on 12th February (fully frozen state), 24th, 26th, 29th, 30th March (thawing period), 1st, 6th, 15th April (recovering period), 6th May 7th July and 12th October 2010.

Typical seasonal variations in pavement stiffness in northern regions can clearly be seen with the deflection basin. Figure 5 shows variations in deflection basin during year 2010 measurements at the Torpsbruk site. As can be seen in this Figure, in winter, the pavement structure is very stiff and therefore the maximum deflection is very small (<100 microns). This is due to the frozen base and subbase and the upper part of the subgrade as well as the low-temperature stiff HMA layer. As the spring-thaw period starts, thaw gradually penetrates the pavement structure and consequently deflection increases. Basin was deepest when the thaw completed by 1st of April which indicates that pavement was in its softest stage. The deflection basin gradually became shallower as the excess pore-water was drained. The overall deflection of the thawed pavement (558 microns on 1st April) was 40 percent greater relative to recovered summer deflections (399 microns on 7th June) despite the fact that HMA layer was much softer in the summer measurement. The thaw weakening and the recovering can clearly be seen in Figure 5.

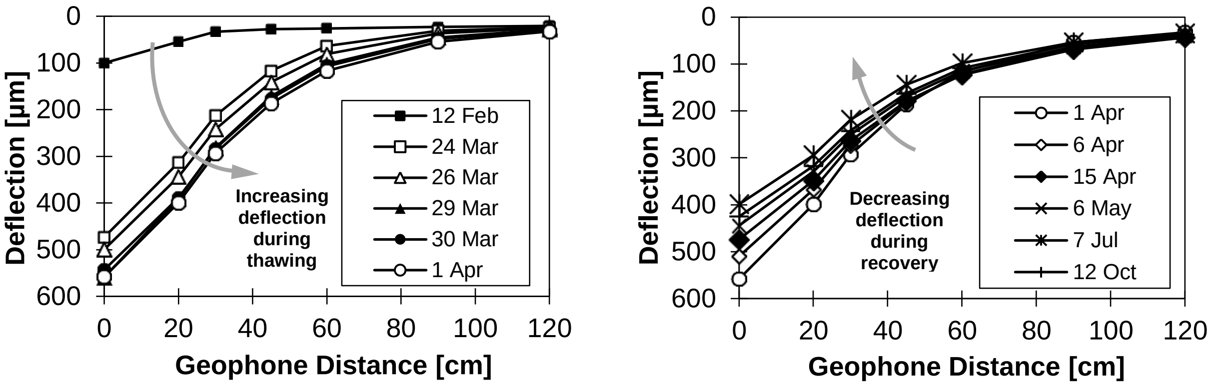

Figure 5: Variations of deflection basin with time during the thawing period (Left) and recovering period (Right) at Torpsbruk site during 2010.

Figure 6 shows the averaged maximum deflection for the 23 measurements at the Torpsbruk site as a function of time. One FWD was performed when the pavement was fully frozen. From Figure 3 it can be seen that the thaw initiated around 10th of March with a quite rapid process. Unfortunately, the second FWD measurement was performed when the thaw had nearly reached the bottom of the subbase layer (45 cm depth). After reaching the maximum deflection by April (completely thawed) the deflections gradually decrease as the layers recover. Considering the pavement maximum deflection, pavement thaw weakening was a rapid process (approximately two weeks) whereas the recovery took place over a longer time period (more than one month).

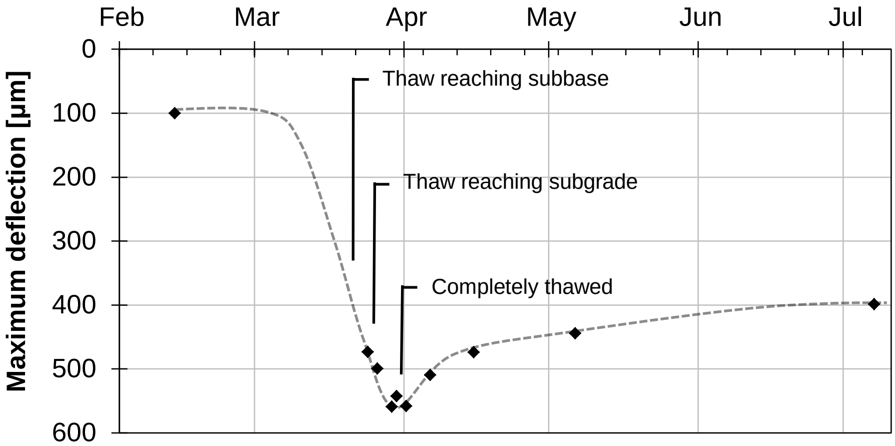

Figure 6: Maximum deflection during 2010 at Torpsbruk site.

5.2 Backcalculated resilient moduli

The computer program Evercalc (Everseries, 2005), developed by the Washington State Department of Transportation, was used for backcalculation of the layer moduli from the FWD deflection data. In the backcalculation process, the base and subbase courses were considered as one single granular layer. The frozen part was considered as a single layer. Number of layers in the backcalculation and their respective thicknesses were chosen based on the thaw penetration at each FWD date.

The modulus value for the HMA course was assigned manually based on its temperature at the time of performing the FWD measurements. With good estimation, the stiffness of the HMA layer was calculated according to:

$$E_T = E_{T_{ref}} . e^{-b(T-T_{ref})} \quad (1)$$

where, E_T is the stiffness of HMA layer at a certain temperature T, T_{ref} is the reference temperature and E_{Tref} is the HMA layer stiffness at the reference temperature. For MABT16 asphalt concrete, T_{ref} = 10ºC, E_{Tref} = 6500 MPa and b = 0.065 (Erlingsson, 2010b). The maximum (unfrozen) and the minimum backcalculated layer stiffness for the granular layer and the subgrade are presented in Table 1. The lowest stiffness value corresponded to the 24th of March measurement when the pavement was almost completely thawed. The maximum stiffness values referred to the 7th of July measurement when the pavement had fully recovered. The subgrade showed greater reduction in the stiffness during the spring thaw than the granular base and subbase layers. The subgrade stiffness in summer was 2.7 times its thawed value in spring. This ratio was 1.91 for the granular layer.

Table 1: Recovered summer and spring thaw pavement layer stiffness from backcalculated FWD measurements.

Layer	**Stiffness (MPa)**		**Spring Thaw Stiffness Decrease (%)**
	Summer	**Spring Thaw**	
Base and Subbase	279	146	48
Subgrade Soil	152	56	63

5.3 Resilient modulus-moisture relationship

The backcalculated layer moduli and the moisture content variations in the subbase layer and the subgrade are presented in Figure 7. The decreasing trend in granular layer modulus (base and subbase) with thaw progression and increase in moisture content is seen in Figure 7 (left). As the moisture content gradually decreased from late March, the layer modulus increased. The modulus reached its maximum value (279 MPa) in July when the excess moisture from thawing had fully drained from the pavement structure. It should be mentioned that the position of the uppermost moisture sensor was nearly at the bottom of the subbase layer. Nevertheless, the correlation of the granular layer moisture content and its respective stiffness modulus is apparent.

A clear correlation between the moisture content and backcalculated subgrade modulus can be seen in Figure 7 (right). When the moisture content in the subgrade reached the maximum values (29 percent at 90 cm and 33 percent at 120 cm depth) on the 23rd of March, the subgrade modulus experienced its minimum value during the spring thaw period (56 MPa). The main significant increase in the subgrade modulus occurred from late March to early May, when the moisture content of the thawed pavement structure also decreased rapidly. The modulus still increased toward late spring but at a slower rate.

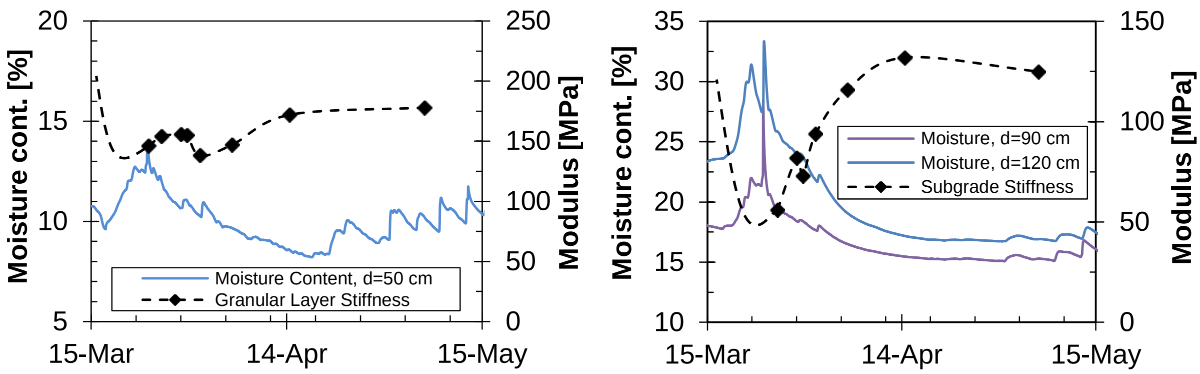

Figure 7: Backcalculated moduli and volumetric moisture versus time for granular layer (left) and subgrade (right) during 2010 at Torpsbruk site.

5.4 Deflection basin indices

Deflection basin indices can provide an indication for the mechanical behaviour of the pavement (Horak and Emery, 2006). FWD data was utilized to analyse the Surface Curvatures Index (*SCI*), Base Curvature Index (*BCI*) and Subgrade Strength Index (*SSI*) during the spring thaw and the recovery periods (Table 2). The *SCI* is the characterizing factor representing the stiffness of the upper part of the pavement structure. The *SCI* for the recovered pavement had decreased by 35 percent compared to the recently thawed value in late March (Figure 8a). The *BCI* is the curvature of the outer part of the deflection basin and mainly represents the stiffness of the bottom part of the pavement (subbase course) and/or upper part of the subgrade soil (Doré and Zubeck, 2008). From April to July 2010, the *BCI* value showed a 33 percent reduction (Figure 8b). The *BDI* represents the lower subgrade layer (Horak, 2008) and showed a 29 percent decrease during the recovery period (Figure 8c). The decrease in the *BDI* was less than the decrease in the *BCI* value. This was in agreement with the measured moisture in Figure 4 showing that the upper section of the subgrade was more affected during the thawing period compared to the lower section.

Another characterization index that appears to represent the bearing capacity of the subgrade soil during spring thaw is the Subgrade Strength Index (*SSI*). It is defined as the ratio of the measured surface deflection from the fifth FWD geophone during thawing period

(d_{900t}) to the measured deflection of the same geophone after recovery (d_{900s}) (Janoo and Berg, 1990). The variation in *SSI* with respect to time is plotted in Figure 8d. Small *SSI* values are related to winter conditions with fully frozen pavement structure (12th of February and 24th of March measurements). With progression in thawing, the *SSI* value rapidly increased with the peak value of 1.3 in the mid-April measurement. The *SSI* value then gradually decreased at a slower rate to the summer value during the recovery period. It can be seen that the *SSI* did not show significant changes until the thaw depth reached the subgrade on the 26th of March.

Table 2: Deflection basin indices (Modified from Horak, 2008).

Deflection Basin Index		**Description**
Surface Curvature Index	$SCI = d_0 - d_{300}$	Curvature of the inner portion of the basin. Indicates the stiffness of the top part of the pavement.
Base Curvature Index	$BCI = d_{300} - d_{600}$	Curvature of the middle part of the basin. Indicates the stiffness of the bases of the pavement.
Base Damage Index	$BDI = d_{600} - d_{900}$	Curvature of the outer part of the basin. Indicates the stiffness of the bottom part of the pavement or the top part of the subgrade soil.
Subgrade Strength Index	$SSI = d_{900_t}/d_{900_s}$	t indicates measurement during thawing and s indicates measurement after thaw recovery.

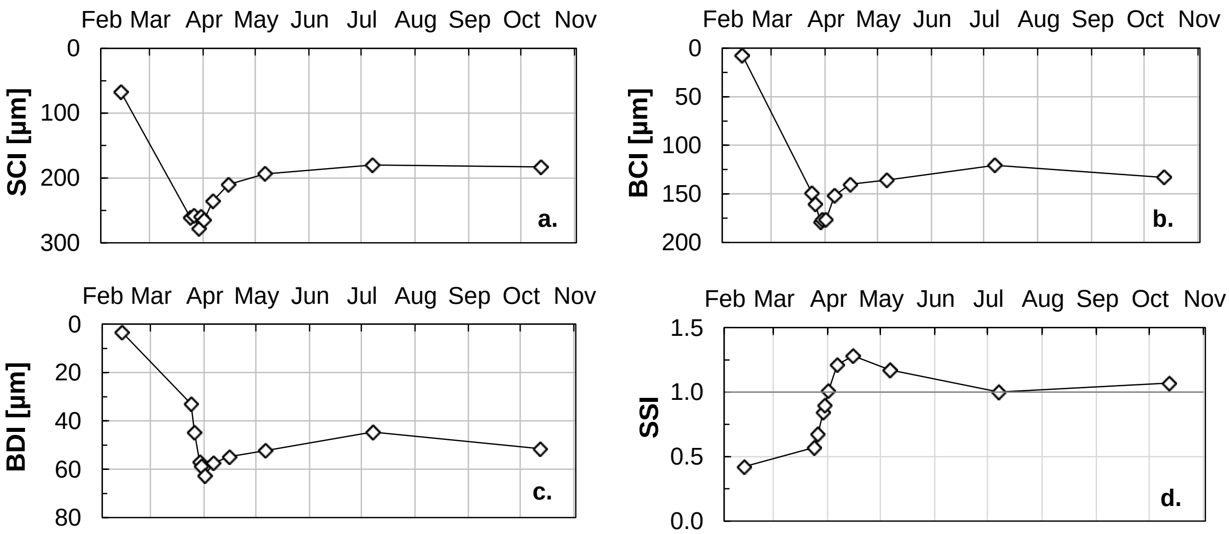

Figure 8: Variation of deflection basin indices with time during thawing and recovery periods in 2010 at Torpsbruk site.

6 SUMMARY AND OBSERVATIONS

A field study was carried out in which a rural county road with thin flexible pavement was instrumented with in order to monitor changes in layer moduli caused by seasonal variations in environmental factors. The instrumented site was located in the southern part of Sweden and experienced 1.2 m frost penetration during the study period. Subsurface temperatures, moisture phase and moisture contents were recorded regularly throughout the study with main focus to capture the spring thaw phenomenon. The stiffness of the pavement structure was assessed during this period using a FWD. Pavement layers moduli were determined from the deflection data using the program Evercalc. The moduli were further analysed with respect to the environmental factors.

The deflection data indicated that the pavement was very stiff when the frost penetrated the base, subbase and the subgrade soil. The pavement stiffness reduced significantly as thaw penetrated the structure during early spring. Evident correlation between the unfrozen moisture content and the layers moduli were observed. Liquid moisture content of all layers increased rapidly during the entire thawing which can likely address the loss in stiffness. Pavement experienced its softest condition as thawing completed and high annual moisture was registered. Thereafter, the pavement gradually regained its prefreezing stiffness as the excess thawing-water drained out from the structure. When thawing was complete, the modulus of the granular layer and subgrade decreased by about 48 percent and 63 percent of their summer values respectively.

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