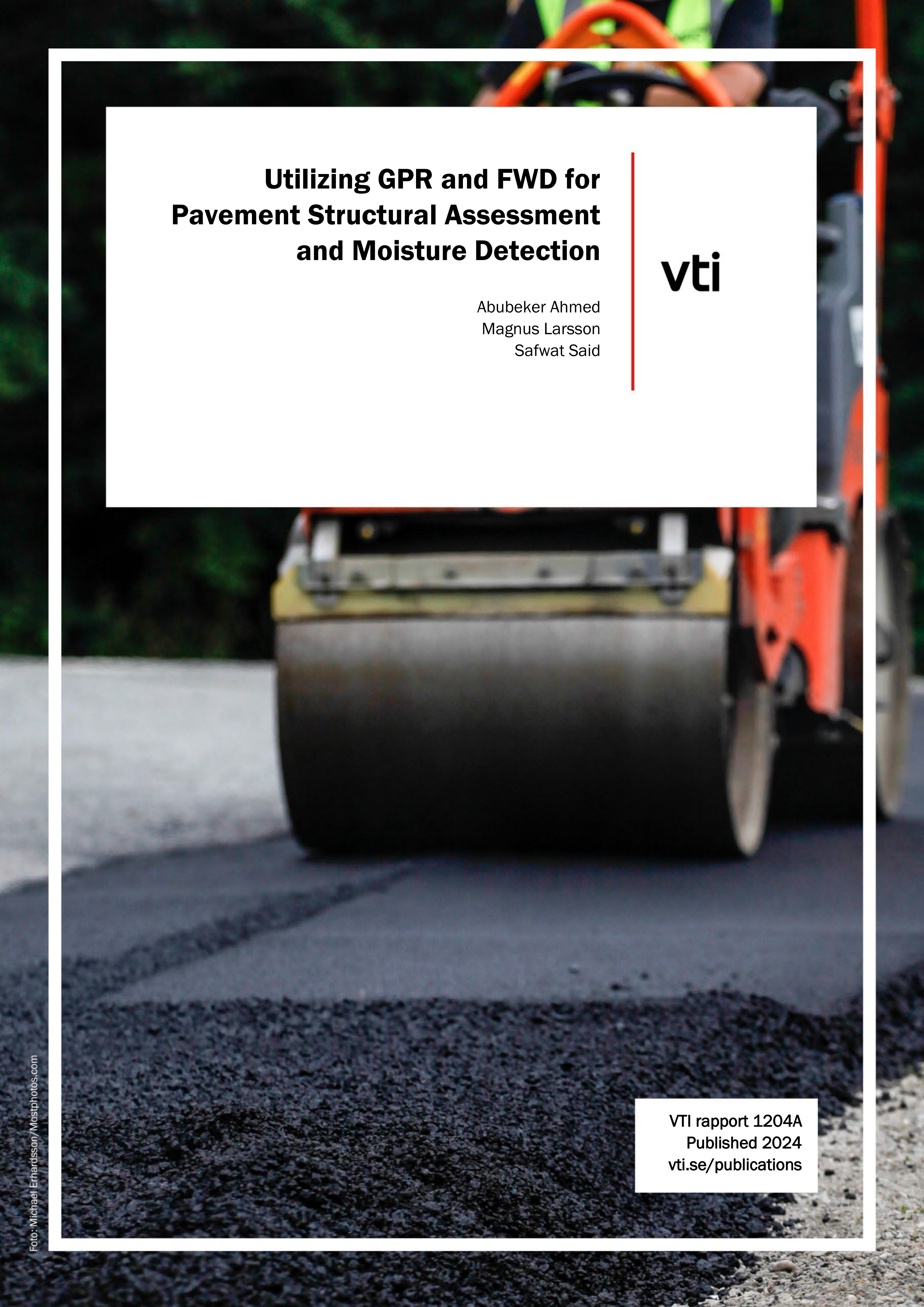

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Kort sammanfattning

Tillståndet hos vägöverbyggnader påverkas bland annat av förekomsten av vatten och fukt i vägkonstruktionen. Förekomst av vatten accelererar nedbrytningen av vägen och leder till dyra underhållskostnader. Forskningen har visat att betydande vägandelar behöver tidigarelägga underhållsåtgärder, oavsett trafikvolymen på grund av fuktrelaterade skador. Övervakning av fuktförhållanden i synnerhet med icke-förstörande och kontinuerliga metoder är därför bra att ha vid val av lämplig underhållsåtgärd. Dessutom är det värdefullt att känna till fukttillståndet i vägen för en mer korrekt bedömning av bärighetsmätningar med FWD (fallviktapparat) eller TSD (Traffic Speed Deflectometer), särskild under våren (upptiningsperiod). I denna studie används en flermottagande markradar (GPR) och en fallviktsdeflektometer för bedömning av fuktnivåer och strukturellt tillstånd för en fullskalig vägkonstruktion inomhus. Grundvattennivåer i vägkonstruktionen varierades genom tillförsel av vatten i testkonstruktionen.

GPR-mätningarna rapporterar en relativ vattenhalt i testkonstruktionen. Resultaten visade en uppenbar korrelation mellan fallviktsmätningarna och de genomsnittliga GPR-hastighetsmätningarna för de undersökta testerna. Vidare forskning av andra GPR-parametrar, såsom frekvens, magnitud och amplitud för GPR-signalen, rekommenderas.

Nyckelord

GPR, FWD, fukthalt, fuktskador.

Abstract

Asphalt pavement performance is affected by the presence of water(moisture). Increased moisture within the road structure can result in substantial cost increase for the for society. Research have showed that significant portion of the road sections need early maintenance measures regardless of traffic volume due to moisture-related damages. Monitoring moisture conditions, preferably using a non-destructive continuous method, offers important information into the decision-making and selecting appropriate maintenance intervention. Furthermore, understanding moisture conditions is critical for accurately interpreting automatic road condition measurements, especially during the spring (thawing) when the roads exhibit the lowest load bearing capacity due to increased levels of moisture.

This study employed a multi-receiver ground penetrating radar (GPR) and a falling weight deflectometer (FWD) devices to assess moisture levels and structural condition of field and indoor full-scale test roads. The groundwater level of the test road was varied by introducing water to the system.

The results revealed an apparent correlation between the FWD and the average GPR velocity measurements. The GPR measurements provided a relative water content of the test roads. Further exploration of other GPR parameters, such as frequency, magnitude, and amplitude of the GPR signal is recommended.

Keywords

GPR, FWD, moisture content, moisture damage.

Sammanfattning

Tillståndet hos vägöverbyggnader påverkas av förekomsten av vatten och fukt i vägkonstruktionen, vilket accelererar nedbrytning av en väg och kan medföra dyra underhållskostnader. Tidigare forskning visade att 10 % av vägarna behöver beläggningsåtgärder på kortare tid än 5 år oavsett trafikvolym. Fukt och vatten i vägkonstruktion är kritiska parametrar för motstånd mot hållbarhetsnedbrytning. På en typisk vägkonstruktion i torrt tillstånd och en vattennivå på 40 cm alternativt 3 cm under terrassen kan resultera i 25 % respektive 50 % större deflektioner vid en belastning på 50 kN. Kännedom av fuktförhållanden vid bärighetsmätningar i synnerhet med icke-förstörande och kontinuerlig metod är därför avgörande vid val av lämplig underhållsåtgärd. Det är värdefullt att känna till fukttillståndet i vägen för en mer korrekt bedömning av bärighetstillståndet i en vägkonstruktion med utrustningar såsom FWD (fallviktsapparat) och TSD (Traffic Speed Deflectometer), särskild under våren (upptiningsperiod).

I denna studie har mätningar utförts med en flermottagande georadar (GPR) och en fallvikts-deflektometer på en fullskalig vägkonstruktion inomhus och på två vägsektioner i fält. Grundvatten-nivåer i vägkonstruktionen varierades genom tillförsel av vatten i testkonstruktionen inomhus. Genom GPR-mätningarna rapporteras en relativ vattenhalt i testkonstruktionen. Målet är att utvärdera vägkonstruktionernas tillstånd under påverkan av vatten/fukt genom fallviktsdeflektioner. Resultaten visade en god överensstämmelse mellan de uppmätta FWD-deflektioner och de genomsnittliga GPR-hastighetsmätningarna med avseende på fuktförhållandena för de testade konstruktionerna. Medan GPR-hastigheten visade sig vara en praktisk indikator för detektering av fukt i vägkonstruktionen, rekommenderas vidare forskning av andra GPR-parametrar, såsom frekvens, magnitud och amplitud för GPR-signalen.

Summary

Asphalt pavement performance is affected by the presence of water and moisture in the road. High moisture within the road structure can result in substantial costs to society. Research have showed that significant portion of the road sections need early maintenance measures regardless of traffic volume due to moisture-related damages. Monitoring moisture conditions, preferably using a non-destructive continuous method, is vital to the decision-making and selecting appropriate maintenance intervention. Furthermore, understanding moisture conditions is critical for accurately interpreting automatic road condition measurements, especially during the spring (thawing) when the roads exhibit the lowest load bearing capacity due to increased levels of moisture.

This project employed a multi-receiver ground penetrating radar (GPR) and a falling weight deflectometer (FWD) measurements to assess moisture levels and structural condition of field and indoor full-scale test roads. The groundwater level of the test road was varied by introducing water to the road systems. For the field sections, two rounds of GPR and FWD campaigns, i.e., for the dry and wet conditions, were conducted. For the indoor facility, the following four rounds for GPR and FWD measurements were carried out.

- Case 1: when no additional water (natural moisture state) was present in the structure.
- Case 2: when the groundwater level is 20 cm below the top surface of the subgrade.
- Case 3: when the groundwater level is in the middle of the subbase layer.
- Case 4: the water stored in the pavement was allowed to drain.

The deflections D0 and D1200, along with the asphalt strain calculated according to TDOK 2019:0463 (Trafikverket, 2020), are analysed for the FWD measurements while the GPR velocity was investigated for the GPR measurements.

The FWD deflection at sensor location D1200 was used to indicate the presence of moisture in the studied test structures. The strain at the bottom of the asphalt layers was also evaluated to investigate its sensitivity to increased groundwater levels. As shown in the results, the TDOK 2019:0463 model produced results that are in a very good agreement with the measured strains as shown in the measurements at the indoor full-scale facility. In general, the strain in the asphalt increased as the groundwater level increased.

The results revealed an apparent correlation between the FWD and the average GPR velocity measurements. The GPR measurements provided a relative water content of the test roads. Further exploration of other GPR parameters, such as frequency, magnitude, and amplitude of the GPR signal is recommended.

Foreword

This report presents the main results of the project “Utilizing GPR and FWD for Pavement Structural Assessment and Moisture Detection”. The project was funded by the Swedish Transport Administration and VTI.

Farhad Salour, Trafikverket was the contact person for the project and I appreciation his active participation during the execution of the project. Magnus Larson, WSP and Mikael Bladlund deserve recognition for their hard work and efforts during the GPR and FWD campaigns. I would also like to acknowledge Yared Dinegdae, VTI, for his constructive feedback and suggestions.

Linköping, December 2023

Abubeker Ahmed
Project leader

Granskare/Examiner

Sigurdur Erlingsson, VTI.

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1. Background

1.1. Moisture in pavements

The performance and durability of asphalt pavements is adversely affected by the presence of water or moisture within the structure, which eventually leads to great costs to society as maintenance measure will increase. Previous research revealed that, 10% of roads need paving measures in less than 5 years regardless of traffic volume (Lang and Svensson, 2012). Such early maintenance can be related to durability due to repeated traffic loading in combination with shortcomings in the execution of paving work. Moisture or water in the road structure is also critical factor affecting the performance of asphalt pavements. Information regarding the moisture condition is thus one of the key inputs in the pavement design processes (Rahman et al., 2022, Rahman and Erlingsson, 2016).

Previous investigations of road structures at VTI's full-scale test facility and field sections using the falling weight deflectometer test (FWD) clearly indicated the adverse effects of water on the road structure (Erlingsson, 2010, Saevarsdottir and Erlingsson, 2013, and Fladvad and Erlingsson, 2021). FWD deflections on the pavement surface increased significantly in the presence of water and have a significant impact on service life (Salour et al. 2015, Sulejmani, 2020). Thus, knowledge of moisture and water conditions during deflection measurements using FWD/TSD (Traffic speed deflectometer) is of great importance for the analysis/interpretation of the measurement data as well as for the selection of appropriate maintenance measures. This will also permit FWD/TSD or other automatic road condition measurements during the spring (thawing) period when roads often have the lowest load capacity due to increased level of moisture. Therefore, the monitoring of water conditions using a non-destructive continuous test method in conjunction with FWD/TSD measurements is vital. The moisture measurements can form a basis for identifying locations for a detailed load-bearing destructive and/or non-destructive investigations, which in turn can be used to assess the structural condition of the road and to suggest appropriate maintenance measures.

The water content of road materials can be measured using different methods. The methods can be either stationary (or point measurement) or continuous. The stationary moisture measurement methods include laboratory tests of drilled specimens, capacitance-based methods, resistivity-based methods, and Time Domain Reflectometry (TDR). TDR is the most commonly used method among the stationary moisture monitoring techniques (Salour and Erlingsson, 2012). The continuous moisture monitoring techniques collect continuous moisture data along the length of the road. These methods include thermal camera method and ground penetrating radar (GPR). GPR-based methods are commonly used for continuous road moisture survey. The GPR antenna can be either air coupled, or ground coupled, depending on the way the antennas are mounted with respect to the ground surface. The air coupled GPR permits surveying at a higher traffic speed. This report focuses on the GPR methods using the air coupled antennas. Furthermore, depending on the number of receivers in the GPR unit, different analysis methods can be adopted, i.e., surface reflection method (one receiver only) or coreless GPR (multi-receiver). The measurements from the surface reflection method are limited to thicknesses of roughly the top 25–40 mm depending on the antenna's frequency (Arnold et al., 2017). In coreless GPR, the travel time shift recorded at each receiver for the electromagnetic wave reflected from a specific boundary is determined. This time shift leads to the calculation of the layer thicknesses and the average wave velocity (average dielectric value).

Relatively accurate values of layer thickness and average dielectric constant can be found using the coreless GPR (Wright et al, 2014). However, a high resolution GPR unit is required to achieve the accuracy and a skilled GPR operator is needed to process the data (Arnold et al., 2017). The present study focuses on the coreless GPR (two receivers) method to monitor the moisture condition in road pavement layers.

1.2. Objectives and scope

The objective of the project is to evaluate whether GPR and FWD measurements can be employed to identify road sections with poor structural conditions mainly due to insufficient drainage conditions or increased moisture content in the pavement layers.

To achieve the objectives and to quantify the pavement structural conditions, FWD and GPR measurements are carried out on two field road sections and one test road structure in an indoor full-scale test facility. The goal is to evaluate the performance of pavement structures under the influence of water. The moisture or water content of the road sections are assessed using the GPR measurements and the structural condition of the roads will be evaluated using the FWD measurements under different groundwater or moisture levels.

2. Description of roads sections

2.1. VTI test road

The VTI test bed (also called “Cykelbana”) is an old test road located at VTI Linköping. It was constructed in the 1980s for various types of road research activities. However, the road has not been actively used in recent years. The test road is about 30 m long, and a well was drilled on the outer edge of the road. The moisture/water content of the pavement layers was adjusted by supplying water through the well, thereby affecting the groundwater in its near vicinity. Moisture measuring rods were installed at the two ends of the test road and on the opposite side of the well. The moisture rods were used to measure the moisture content of the different pavement layers. Ground penetrating radar (GPR) and falling weight deflectometer (FWD) tests were conducted on the test section under wet and dry conditions. The GPR and FWD measurements were carried out simultaneously. A detailed description of the instrumentations and the GPR measurements can be found in Nordin et al. (2022). The FWD tests were conducted every 2.5 m.

Figure 1 shows the test section. The red circles on the image show the points where the FWD test was carried out and M-1 and M-2 are the locations of the moisture sensors. The FWD and GPR measurements close to the well and moisture sensor 1 (M-1) are expected to be affected by the change in the well. Whereas the measurements close to moisture sensor 2 are not expected to be affected thus are considered as reference section.

Figure 1. Layout of the test road (Photo: Google Earth).

2.2. Road 126 in Torpsbruk

Road 126, situated North of Torpsbruk in Alvesta municipality, Southeastern Sweden, is a two-lane rural road. The road corridor is characterized by high groundwater level due to elevated topography and the potential downward flow of groundwater beneath the road corridor. Thus, a research project was initiated to investigate mechanisms that would lower the groundwater level. Accordingly, a subsurface drainage system, consisting of a synthetic polymer core surrounded by geotextile filters with perforated collective pipes at the bottom, was installed along a 250 m long stretch of the road section (Bäckman, 1986). The installation successfully lowered the ground water along the road section. A detailed description of the drainage installations can be found in Bäckman (1986). Moreover, the road section was equipped with moisture sensors, groundwater level measurement and frost rod. A detailed description of the various types of instrumentations can be found in Salour and Erlingsson (2012). The deep drainage system in the northbound section of the road was fitted with an installation that allows the manipulation of the groundwater level or moisture content in the pavement layers (Nordin et al., 2022). Closing the drainage facility increases the water content.

GPR and FWD tests were carried out on the road section under dry and moist conditions. The detailed description of the GPR campaign and the groundwater level measurements can be found in (Nordin et al., 2022). This report presents the FWD results and their correlation with the GPR measurements.

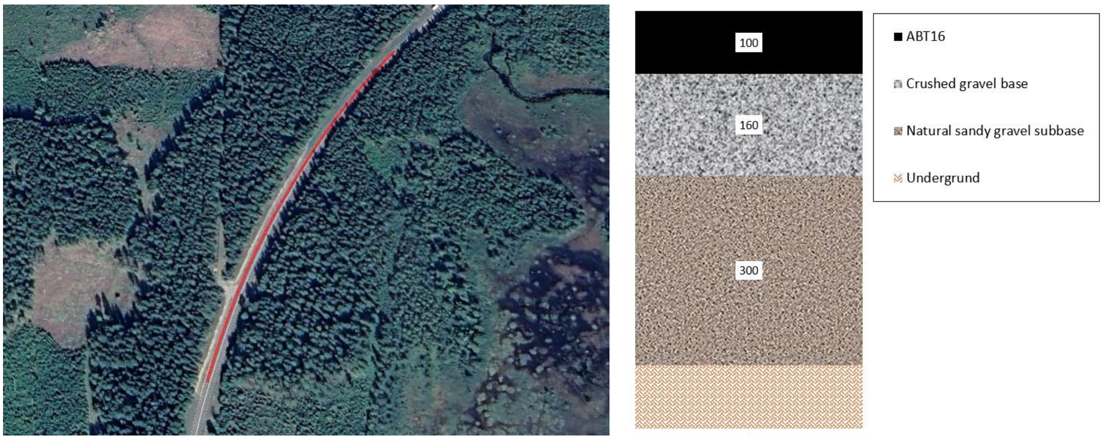

Figure 2. Road 126 Torpsbruk site (left, Photo: Google Earth) and cross-section of the road (right), numbers in the figure indicate the thickness in mm.

2.3. Indoor full-scale test facility

The VTI indoor full-scale test facility has three test pits that are 3 m deep, 5 m wide and 15 m long (Wiman, 2010, Saevarsdottir et. al., 2016). The sides and the bottom of the test pits are made of concrete. The groundwater level in the test pits can be varied by adding water to the pavement structure through an installation at the bottom of the pavement structure. Additionally, the pavement structures constructed in the test pits are usually instrumented with various types of sensors such as strain gauges, temperature, and moisture sensors. The GPR and FWD measurements were carried out on a pavement structure constructed for another project. The pavement structure was instrumented at the bottom of the asphalt layers with asphalt strain gauges (ASG). The GPR and FWD measurements were carried out at different ground water levels. The strain responses of the strain gauges under FWD loading were also recorded. The indoor full-scale test facility and the cross-section of the test pavement are shown in Figure 3. The GPR measurements were conducted to detect the moisture conditions in the pavement structure. The FWD/GPR tests were conducted under the following conditions:

- Dry - when no additional water was present (natural moisture state) in the structure.
- Low moist - when the groundwater level is 20 cm below the top surface of the subgrade.
- High moisture - when the groundwater level is 20 cm above the subgrade, or in the middle of the subbase layer.
- Drained – the water stored in the pavement was allowed to drain.

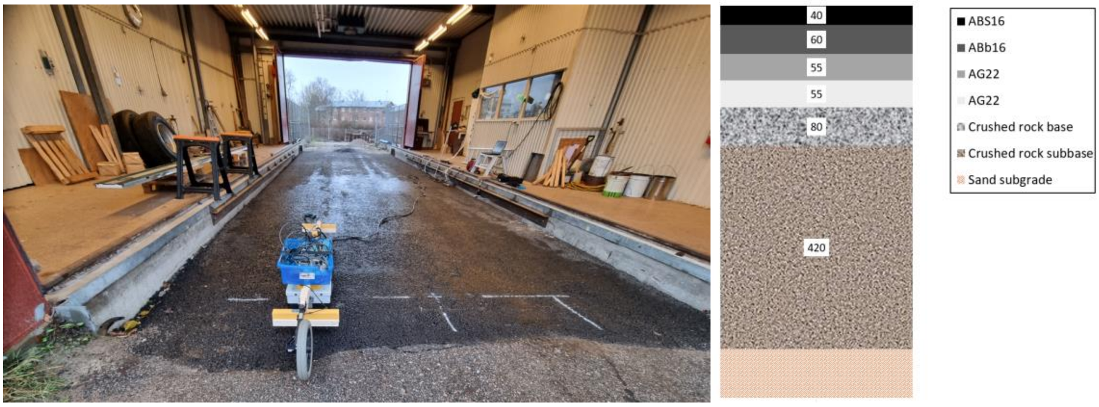

Figure 3. Indoor full-scale test facility at VTI (left, Photo: Magnus Larsson). Cross-section of the pavement structures (right), the numbers in the layers indicate the thickness mm.

Several ASG sensors were installed at different locations within the pavement structure. Figure 4 shows the layout of sensor locations as seen from the top. The black dots in the figure represent the sensors. As can be seen in Figure 4, the pavement structure is divided into three sections. The sections differ in ASG installations in the asphalt layer. The reference section and the associated strain gauges are used for this project. Sensors 1, 2, 3, and 4 are located at the bottom of the asphalt layer. Sensors 1 and 2 are positioned in the longitudinal direction whereas sensors 4 and 5 are in the transvers direction. Sensors 5, 6, 12, 13, 14, and 108, installed in the middle of the asphalt layers and close to other installations, are not considered for this study.

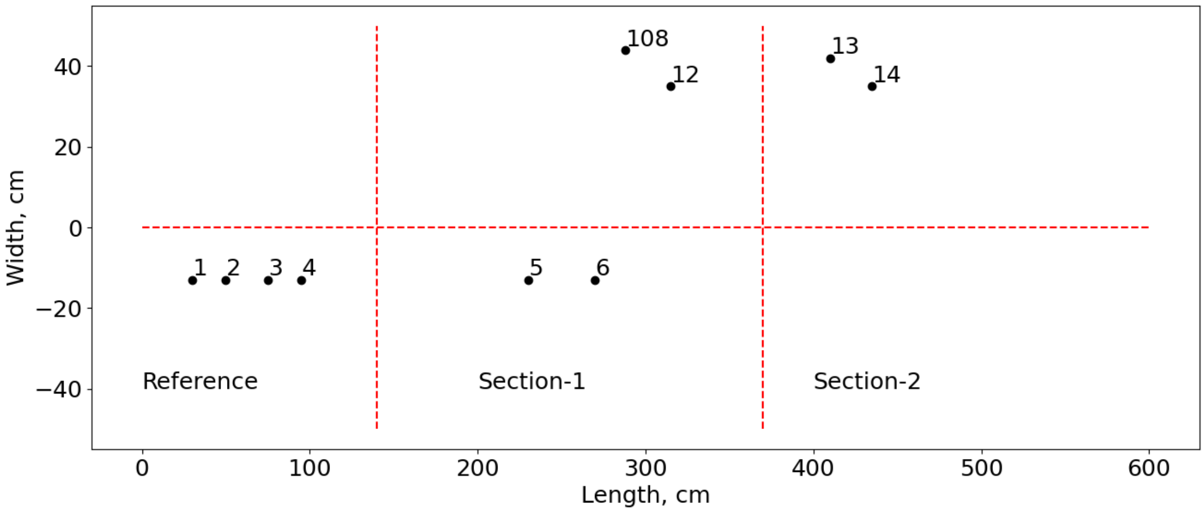

Figure 4. Layout of sensor.

3. Method

3.1. Falling weight deflectometer (FWD)

FWD, which is a non-destructive test method, is used to evaluate the structural condition of pavements. In FWD tests, an impact load of 30, 50 or 65 kN is applied, and the resulting pavement surface deflections are measured. The deflections are measured using geophones placed on the pavement surface. An impact load of 50 kN was used for this work. The deflections are measured at locations of 0, 200, 300, 450, 600, 900, and 1200 mm from the loading centre. Figure 5 shows the FWD test device.

Figure 5. FWD test device (Photo: Hejdlösa Bilder AB/VTI).

The measured deflections and/or derived indices are employed to understand the condition of the pavement. The commonly used deflection and derived indices are listed below:

- deflections, D0, D200, D300, D450, D600, D900, and D1200
- surface curvature index, SCI200 = D0 - D200
- surface curvature index, SCI300 = D0 - D300
- base damage index, BDI = D300 - D600
- base curvature index, BCI = D600 - D900
- basin area, A = 150(D0+2D300 +2D600 +D900)/D0
- radius of curvature, $R = \frac{r^2}{2(D0-Dr)}, r = 1500$
- slope – surface (D0, D200, D300), underground (D600, D900, D1200)
- strain at the bottom of asphalt, $\varepsilon_{a,T}$ = 37.4 + 0.988*D0 – 0.553*D300 – 0.502*D600 (Trafikverket, 22020)
- strain at the bottom of asphalt at 10°C (Trafikverket, 2020) $\varepsilon_{a,10} = \frac{\varepsilon_{a,T}}{\left(\frac{T}{10}\right)^{3.08*10^{-8}*h^2*D_0}}$
- subgrade modulus, $E_u = \frac{52000}{D900^{1.5}}$
- surface modulus, $E_0 = \frac{1000*2*(1-v^2)*\sigma_o*a}{D0}, v = poissos\ ratio, a = plate\ radiu, \sigma_o = contact\ pressure.$

- bearing capacity index (BI), $BI = \frac{1000}{\varepsilon_{a,10}}$
- radius of curvature, $K = \frac{r^2}{2*D0(\frac{D0}{Dr}-1)}$, $r = 600$
- back-calculation of layer moduli.

D0, D200, D300, 600, D900, and D1200, in the list above denotes the deflections at 0, 200, 300, 600, 900, and 1200 mm, respectively. The center deflection D0 indicates the structural condition of the whole pavement structure. Lower D0 indicates good pavement condition. D1200 is commonly used to determine the condition of the subgrade or the layer beneath the superstructure. A stiff underground or subgrade is characterized by lower D1200. An increment in the groundwater level or moisture content in the subgrade is expected to increase the D1200. Table 1 contains the ranges of some of the FWD indices for low, medium, and high-volume roads.

Table 1. Ranges of different FWD indexes (Nilsson, 2020; Boo and Karlsson, 2005).

Parameter	Low volume	Medium volume	High volume
Surface modulus, MPa	220 - 345	350 – 500	500 - 600
Asphalt strain, ε, μm/m	380-550	200 – 350	150 - 200
SCI, μm	280 - 400	125 – 250	75 - 125
BI	2 - 3	3.5 – 6.5	5.5 – 8.5
Radius of curvature, m	70 - 90	100 – 200	250 - 400
Subgrade modulus, MPa	50 - 100	25 – 100	40 - 100

Another way to interpret the FWD deflection measurements is to estimate the layer moduli of the pavement layers through a back-calculation process. Back-calculation is a reverse numerical analysis employed to estimate the layer moduli from the measured deflections.

This report discusses the FWD test results conducted on all test sections under both dry and wet conditions. The deflections D0 and D1200, along with the asphalt strain calculated according to TDOK 2019:0463 (Jansson, 1992, Trafikverket, 2020) are presented and analyzed.

3.2. Ground-penetrating radar (GPR)

GPR is a non-destructive test method used to survey subsurface materials. GPR involves sending a small electromagnetic pulse via a transmitting antenna and registering the reflected signal via a receiving antenna. The travel times of the pulse from the transmitter to the receiver and the properties of the received signal are used to determine the type and/or the composition of the material.

The wave propagation velocity in the soil is strongly influenced by water content. This is because the dielectric constant increases as the water content increases. The GPR method takes advantage of this property for detecting the relative water content. As shown in Equation 1, for soils having low electrical conductivity (resistivity > 100 Ohm), there is an inverse relationship between the dielectric constant and the wave propagation speed. Table 2 presents typical dielectric constants for some commonly used road materials.

Equation 1

$$V = \frac{c}{\sqrt{e_r}}$$

where *V* = wave propagation velocity, *c* = speed of light in vacuum (0.3 m/ns), and, e_r = relative dielectric constant

Table 2. Typical dielectric constants for some commonly used road materials (Davis J.L. and Annan, 1989; Trafikverket, 2014).

Material	**Dielectric constant (-)**
Air	1
Freshwater	81
Dry sand	3–5
Saturated sand	20–30
Silt	5–30
Clay	5–40
Asphalt	4–8
Moraine	8–18
New base and subbase layer	6–9

In this project, multi-channel GPR measurements were conducted to estimate the electromagnetic wave propagation velocity. Two different systems, namely, a MIRA system with 400 MHz antennas, and a ProEx system with 500 MHz antennas were used for measurements at the VTI test road. For measurements at Torpsbruk, however, only the ProEx system with 500 MHz antennas was used. This is because the 500 MHz antennas produce results with a slightly better resolution and the equipment is relatively cheaper (Nordin et al., 2022). A detailed description of the GPR campaign at the VTI test road and the Road 126 Torpsbruk can be found in Nordin (2022).

To investigate the appropriate distance between the transmitter Tx and receiver Rx, data was collected using two different antenna configurations. Figure 6 shows the evaluated two antenna configurations for measurements at the indoor full-scale test facility at VTI. The numbers in the figures indicate the different antenna positions evaluated. In this setup, the travel times of an electromagnetic pulse from the transmitter (Tx) to the receivers (Rx) are registered in all receivers. Then, with the help of the time difference, the speed in the material, which also means that the depth of the interpreted layer can be determined. In this tests, two shielded 500 MHz Malå antennas, a ProEx unit and the Malå Ground Vision software were used. The ProEx unit has functions to "cross-connect" the transmitter and receiver in the two antennas, which means one can simultaneously register four radargrams with different distances between the transmitter and receiver.

A calibration measurement was made to record the different travel times for the "direct wave" between transmitter and receiver. Other measurements can then be adjusted using these travel times. Figure 7 shows the antenna configuration for calibration measurements at the indoor full-scale test facility at VTI.

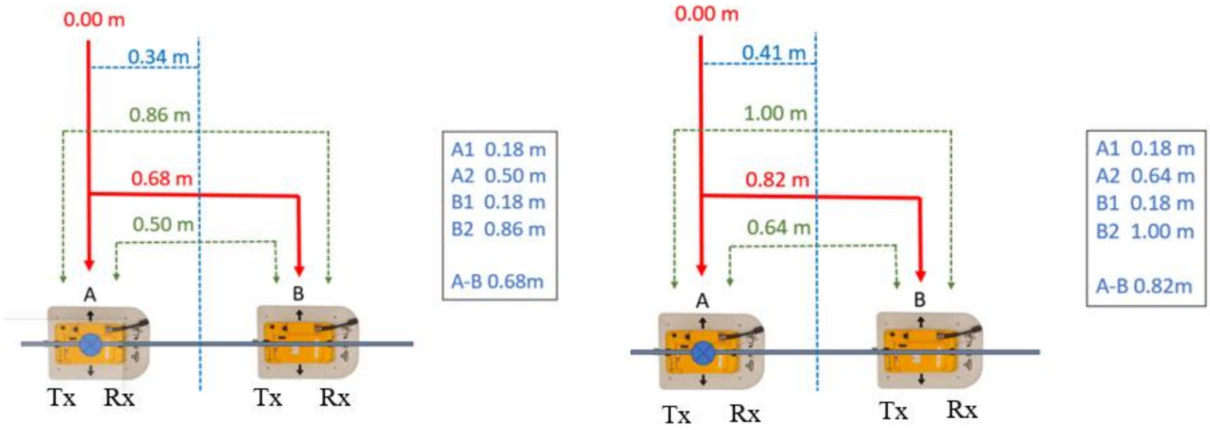

Figure 6. Antenna configurations.

Figure 7. Antenna configuration at the indoor full-scale test facility at VTI (Photo: Magnus Larsson).

3.3. Asphalt strain gauges (ASG)

In addition to the falling weight deflectometer and GPR measurements, asphalt strain gauges installed at the bottom of the asphalt layer were also analysed to determine the condition of the pavement. The H-shaped ASGs were installed on the tested pavement structure at the indoor full-scale facility at VTI. The ASG responses were recorded when the FWD measurements were conducted.

4. Results and discussions

The subsequent section presents the result of the FWD and GPR measurements conducted at the VTI test road, Road 126 Torpsbruk, and the indoor full-scale test facilities at VTI.

4.1. VTI test road

4.1.1. FWD test results

Figure 8 (a) and (b) show the FWD deflection basins in the vicinity of the well where the water was applied to the pavement system and the reference part of the road section (close to moisture sensor 2 (M-2)), respectively. The deflection measurements reveal the effect of moisture on the structural response. The very large center deflection (D0) both at the reference and measurement sections indicate that the road is not in good condition as the road is very old. Figure 9 and Figure 10 show the variation of the D0 and D1200 along the length of the road, respectively. It is apparent from the figures that the increased water content near sensor 1, i.e., where water was applied to the system, showed relatively higher deflections indicating reduced bearing capacity.

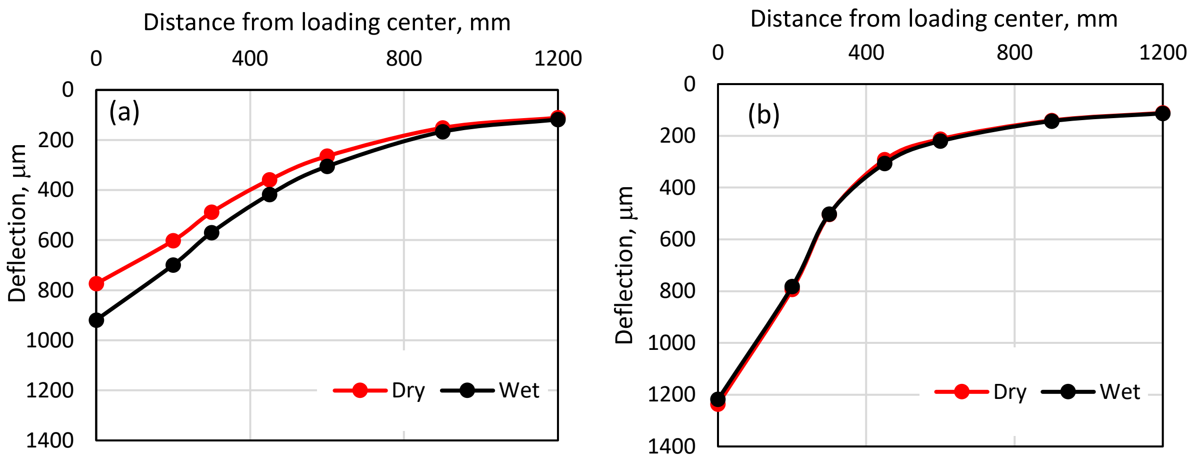

Figure 8. FWD deflection basins (a) close to the well and (b) (farther from the well) the reference section.

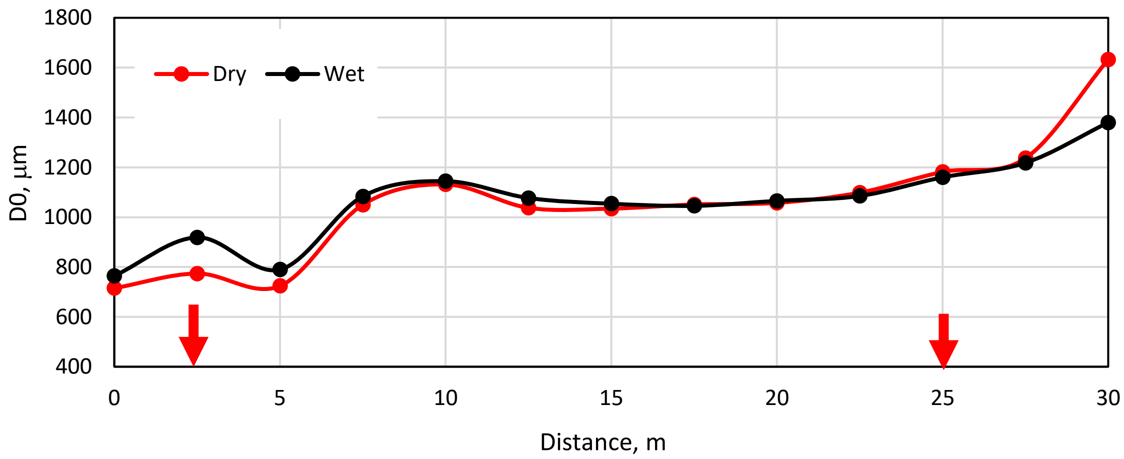

Figure 9. Center deflection D0 for dry and wet condition along the test section. The red arrows indicate the locations of the moisture sensors.

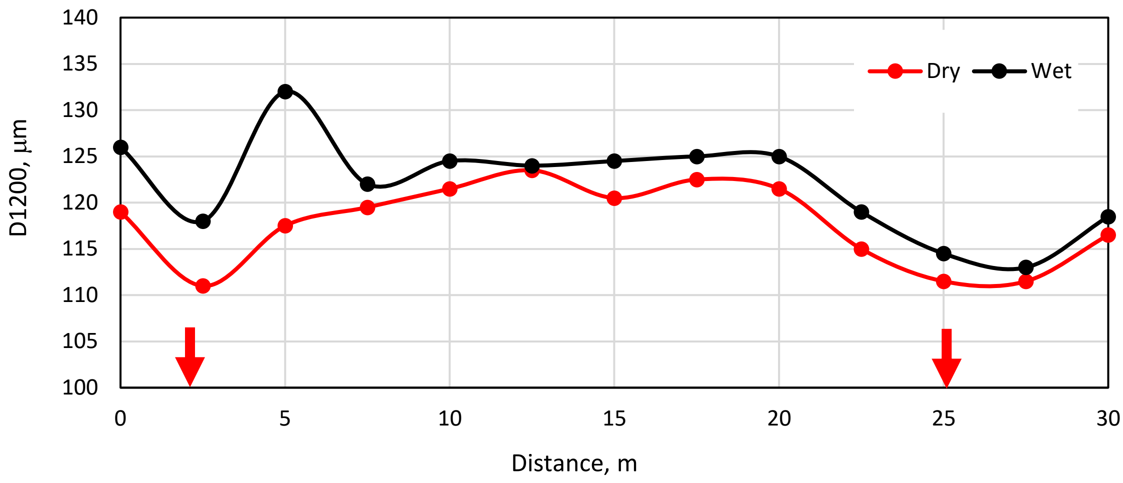

Figure 10. Deflection D1200 for dry and wet condition along the test section. The red arrows indicate the locations of the moisture sensors.

4.1.2. GPR measurement results

The GPR velocity for dry and wet conditions are shown in Figure 11. The section with increased water level produced lower GPR velocity. The difference in the GPR velocity for the reference section was not significant though the velocity for wet conditions was slightly lower indicating the effect of water. This indicates a small amount of water might have travelled to the reference section. This was also evident from the FWD measurements as indicated by the higher D1200 deflection for measurements on wet condition as shown in Figure 10.

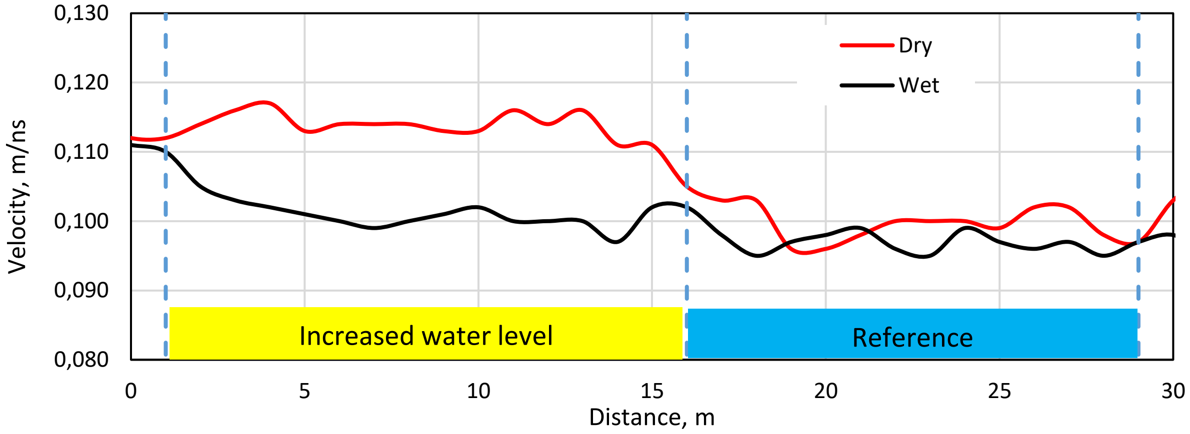

Figure 11. Variation of the GPR velocity along the section for wet and dry conditions.

Figure 12 shows the strain at the bottom of the asphalt layer calculated from the FWD measurements (Trafikverket, 2020). The strains presented are corrected to 10°C since the FWD measurements for dry and wet conditions were conducted at different temperatures, i.e., 20°C and 15°C, respectively. The temperature correction follows the TDOK 2019:0463 recommendation (Trafikverket, 2020). As shown in the figure, the strain for the wet condition is relatively higher. This is evident particularly for the section with the increased water level. The strain for the reference section was in general higher since this part of the road section was in bad conditions with visible surface cracks.

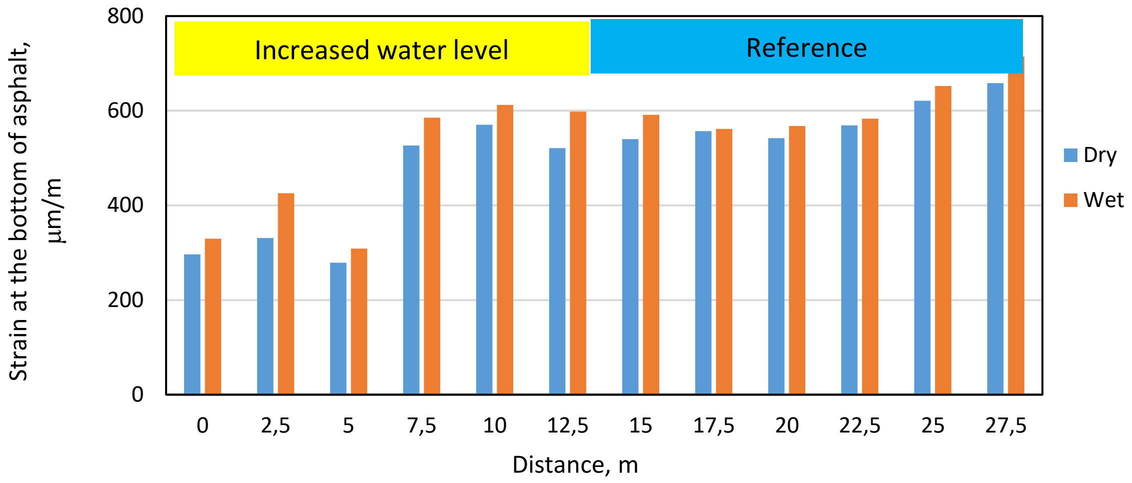

Figure 12. Strain at the bottom of asphalt layer at 10℃ calculated from the FWD measurements for dry and wet condition.

4.2. Road 126 Torpsbruk

The FWD and GPR measurements for Torpsbruk test site under dry and wet conditions are presented in subsequent sections.

4.2.1. FWD test results

Figure 13 and Figure 14 present the FWD deflection D0 and D1200, respectively. The D0 values indicate that the road is in general in good condition and the D0 for the wet condition is slightly higher at the end of the road section (10 – 25 m). This might mainly be because of the increased moisture in the base and subbase layers closer to the clogged drainage pipes. Note that there is a downward gradient of almost 1 meter from the start to the end of the FWD tested section. The D1200 for the wet condition has also increased indicating the effect of the moisture in the subgrade layer. In this case, the effect of moisture was rather uniform over the test sections.

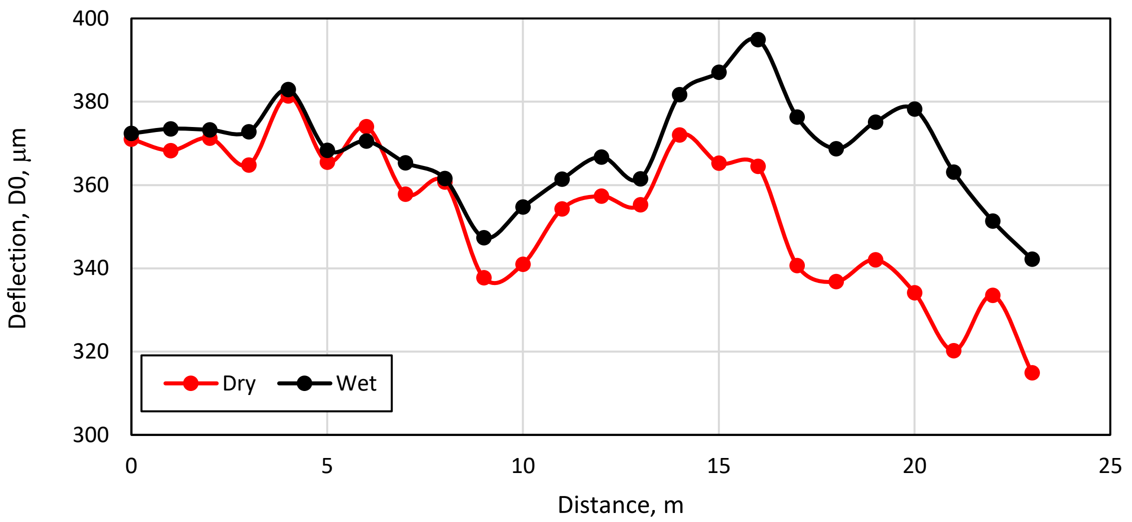

Figure 13. Deflection D0 along the test section for the dry and wet conditions.

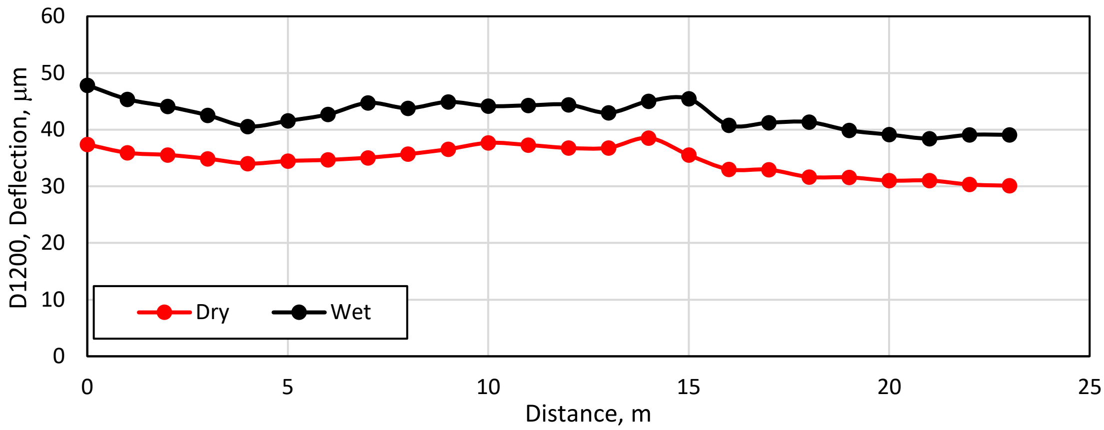

Figure 14. Deflection D1200 along the section for dry and wet conditions.

The strain at the bottom of the asphalt concrete layer was calculated according to TDOK 2019:0463 (Trafikverket, 2020) as shown in Figure 15. It can be seen from the figure that most of the strains under dry conditions slightly exceed or are equal to the strains under wet conditions. This was mainly due to the temperature drop that occurred during the FWD measurements for wet conditions, i.e., the air temperature dropped from 9 to -2°C between the two FWD measurements. The TDOK 2019:0463 equation (Trafikverket. 2020) for adjusting the asphalt strains to 10°C could not be used for FWD measurements below or close to zero. Therefore, FWD back-calculation of the layer moduli was performed to convert the strains to a temperature of 10°C. The thickness of the pavement as reported by Salour and Erlingsson (2014) was used for the back-calculations.

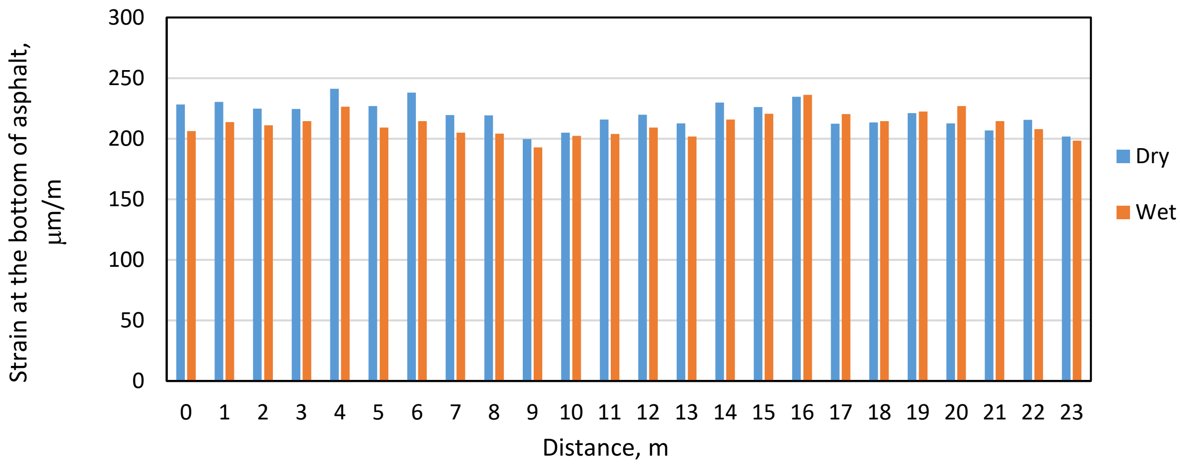

Figure 15. Horizontal strain at the bottom of asphalt layer calculated from the FWD measurements for dry and wet condition. (Note the FWD measurements started when the section was dry at 9 ℃ and ended when the section was wet, and the temperature dropped to -2 ℃).

The back-calculated modulus of the asphalt, base, and subbase (combined), and the subgrade layers are shown in Figure 16 and Figure 17. The back-calculation results revealed that the stiffness of unbound base and subgrade layers decreased for the wet conditions indicating an increased level of moisture in the layers. The back-calculated base and subgrade moduli were comparable to those reported in Salour and Erlingsson (2014). However, the modulus of the asphalt layer has increased because of the temperature drop. Previous research has demonstrated that asphalt materials adhere to the modulus-temperature relationship as defined in Equation 2 (Ahmed and Erlingsson, 2015). Thus, the asphalt modulus - temperature relation (Equation 2), shown in Figure 16 (right), was used to transform the strains in Figure 15 to strains at temperature of 10°C. The strains adjusted to 10°C are shown in Figure 18. It can be observed from the figure that the strains for the wet condition are higher when the effect of temperature is removed.

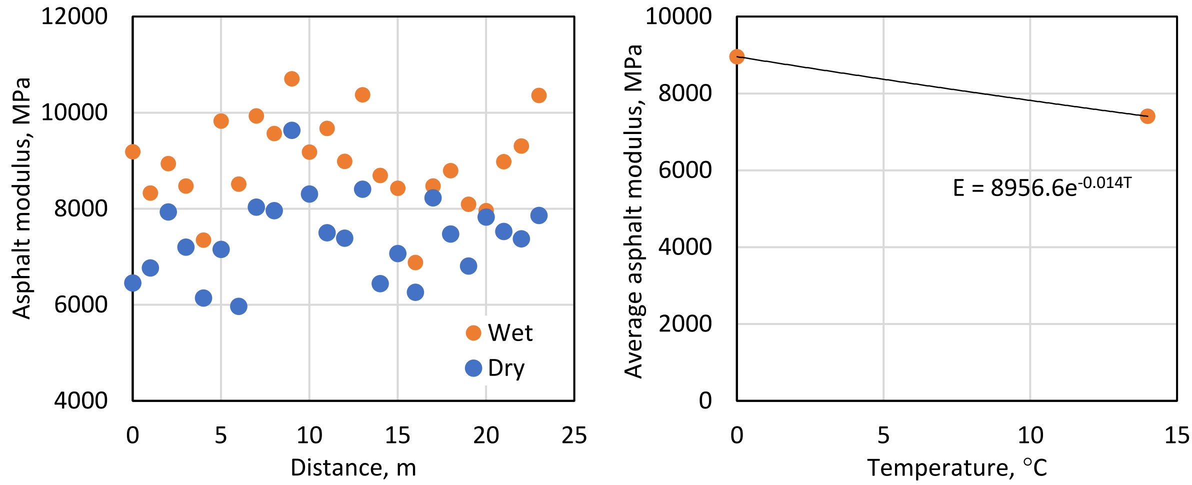

Figure 16. Back-calculated modulus of the asphalt layer (left). Average asphalt modulus vs temperature (right).

Equation 2

$$E_T = E_{T_{ref}} e^{-b(T-T_{ref})}$$

where E_T = the asphalt modulus at temperature T, T_{ref} is the reference temperature (T_{ref} =10°C), b is regression constant.

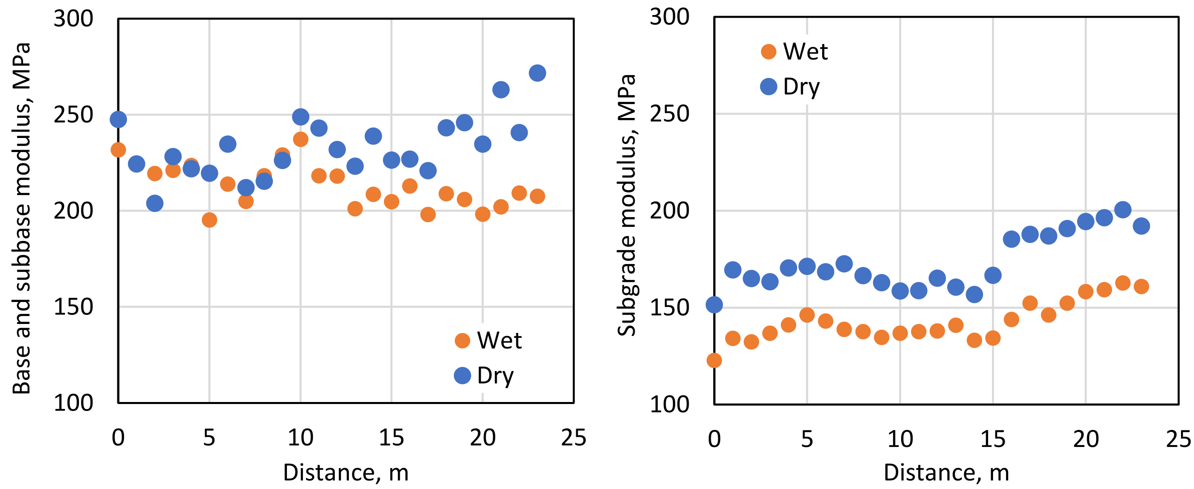

Figure 17. Back-calculated modulus of the base and subbase (left), and subgrade layers (right).

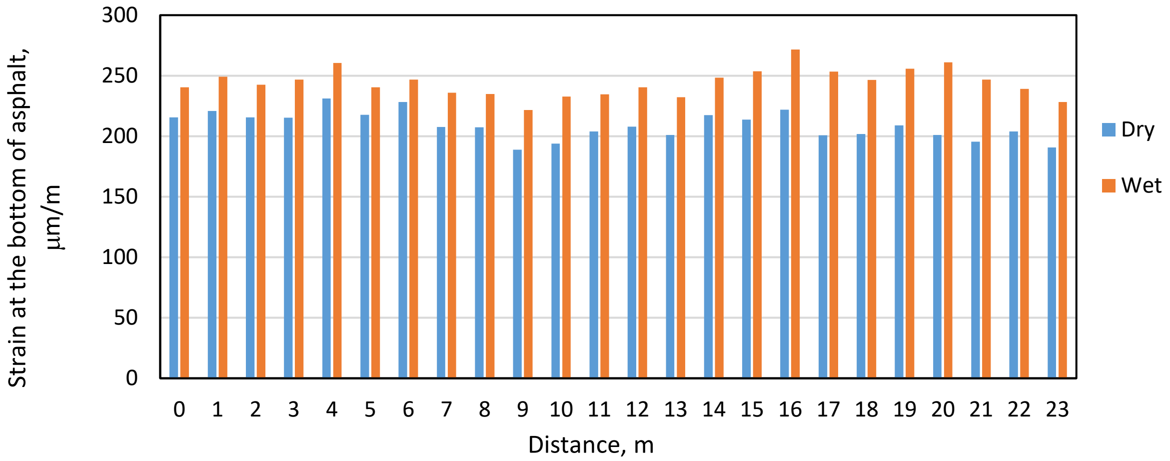

Figure 18. Strain at the bottom of the asphalt layer calculated from the FWD measurements for the dry and wet conditions adjusted to 10 ℃.

4.2.2. GPR velocity results

The GPR velocity measurements for dry and wet conditions are shown in Figure 19. It is obvious that the velocity was reduced for measurements at the wet condition verifying the results of the FWD measurements.

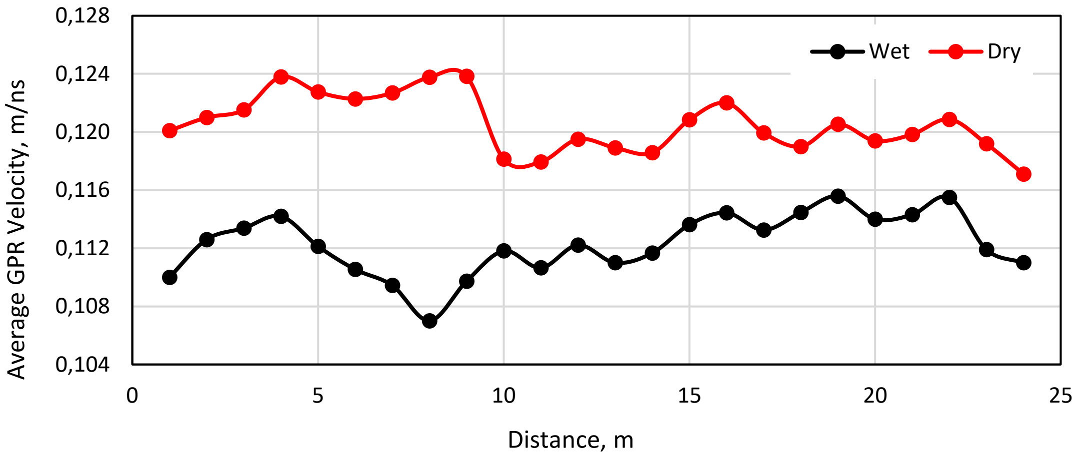

Figure 19. GPR velocity along the length of the test section for the dry and wet conditions.

4.3. Indoor full-scale test facility

An existing full-scale indoor test road section from an ongoing project has been used to conduct the FWD and GPR measurements. The test structure was instrumented with asphalt strain gauges appropriate for this study. The FWD and GPR measurements were simultaneously conducted to detect the moisture condition and its impact. The following sections present the GPR and FWD results under dry, wet, and drained conditions.

4.3.1. FWD test results

Figure 20 shows the FWD deflection basins for dry, wet, and drained conditions. The effect of the different water levels can be seen by looking at the deflections at the remote sensor D1200, i.e., the deflection D1200 increased as the groundwater level raised. The deflection returned to the dry state value when the structure was “almost” completely drained, see Figure 21.

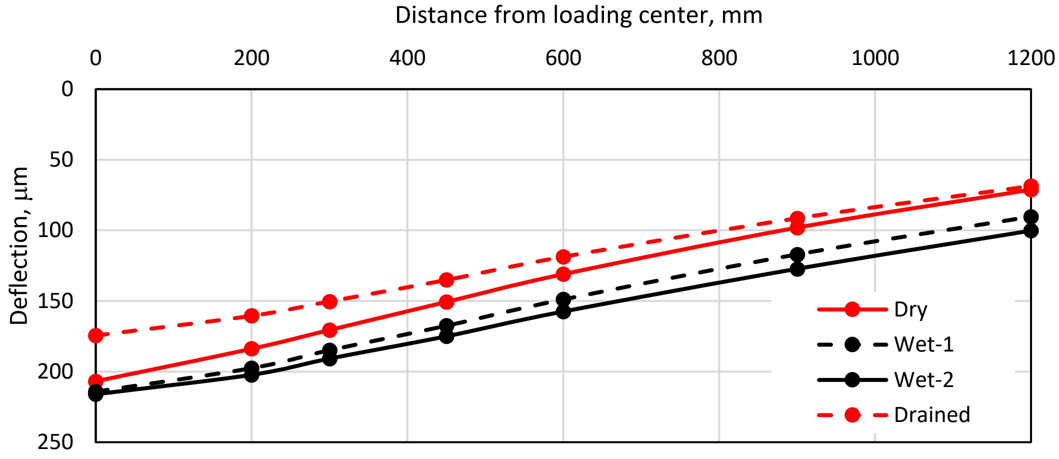

Figure 20. FWD deflection basin for dry, drained and two levels of raised groundwater levels (Wet-1 represents low moist state - when the groundwater level is 20 cm below the top surface of the subgrade. Wet-2 represents high moisture state - when the groundwater level is 20 cm above the subgrade, or in the middle of the subbase layer).

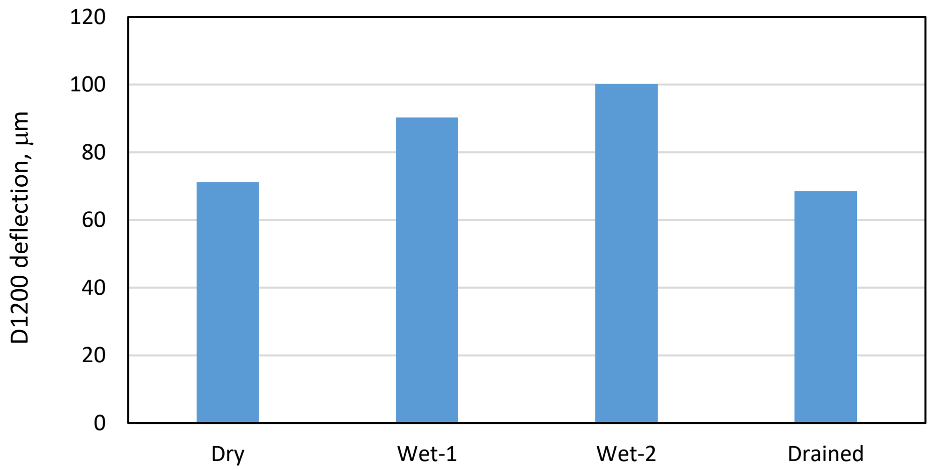

Figure 21. Deflection at D1200 for dry, drained and two levels of raised groundwater levels.

The center deflection D0 decreased for drained conditions as shown in Figure 20. This was due to the temperature drop during the drained test, i.e., the temperature dropped from 12°C to 3°C for the measurements under the drained condition. Thus, to remove the effect of temperature, a back-calculation of layer moduli was performed. The thicknesses of the pavement layers shown in Figure 3 were used for the back-calculation. Figure 22 shows the back-calculated resilient modulus of the base, subbase, and subgrade layers. As can be seen in the figure, the modulus of the subgrade decreased as the groundwater level is raised, which was expected. However, the modulus of the base and subbase layers were not affected by the moisture migration. This might be due to the open grain size distribution of the subbase layer and/or the structural protection from the stiff and thick asphalt layer.

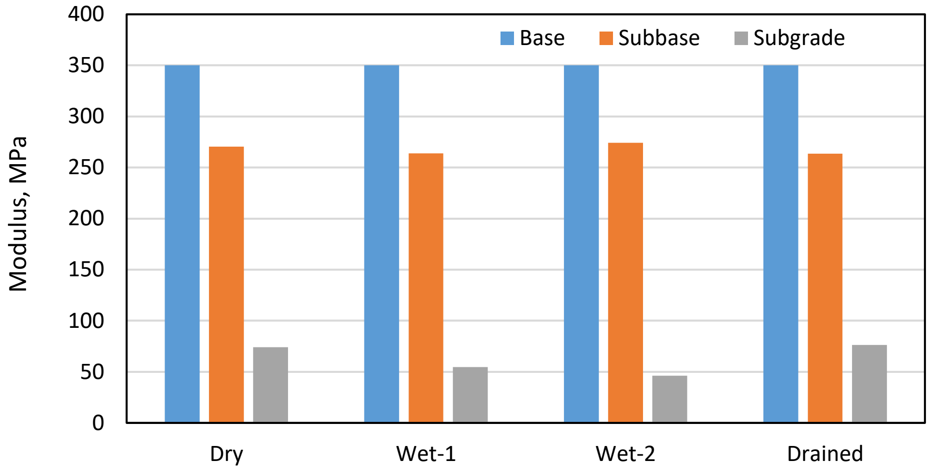

Figure 22. FWD back-calculated resilient modulus of unbound base, subbase, and subgrade layers.

The back-calculated moduli of the asphalt layer for dry, wet, and drained conditions are shown in Figure 23. The effect of the temperature drop is obvious as seen from the increased stiffness of the asphalt layer for the wet and drained measurements. Figure 22 (right) also shows a plot of the modulus at different temperatures. Note that more points are shown in this plot since the back-calculated stiffness from the 65 kN FWD measurements are also included. The data was fitted using an exponential function which is commonly used to express the modulus of asphalt as a function of temperature.

The measured strain using the ASG (Asphalt strain gauge) and the calculated strain using the TDOK 2019:0463 (Trafikverket, 2020) are shown in Figure 24. There is a very good agreement between the measured and FWD calculated strains, and it can be observed that the strains reflected the effect of the temperature drop as shown in Figure 24 (left), i.e., the strains decreased for measurements under wet conditions. Figure 24 (right) presents the measured and calculated strains at adjusted to 10°C. The measured strains were adjusted to 10°C using the modulus-temperature relation (Equation 2) as shown in Figure 23 (right) while the TDOK 2019:0463 method was used to convert the FWD calculated strains at 10°C. Thus, when the effect of temperature was removed, the strain at the bottom of the asphalt increased as the groundwater level is raised.

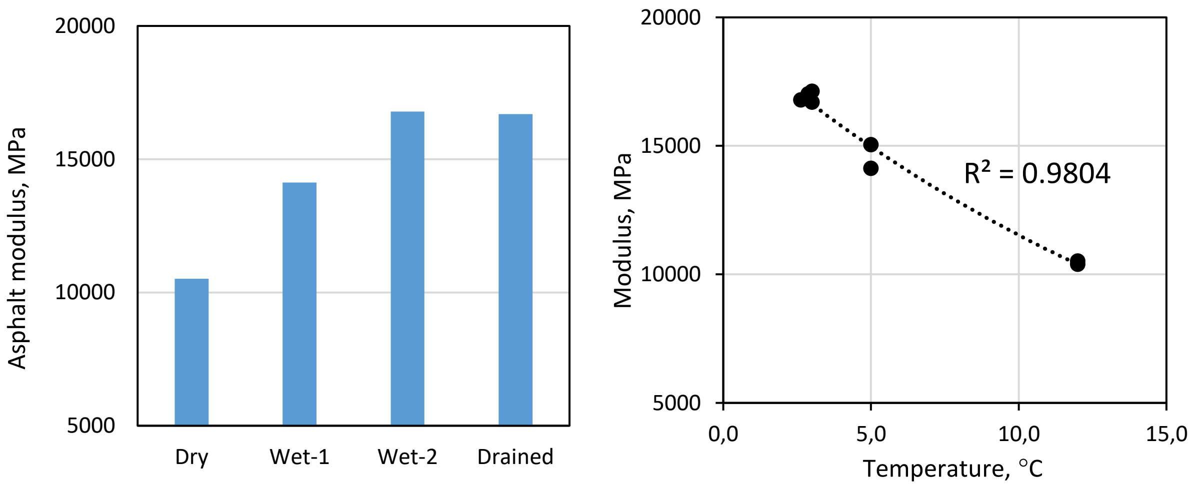

Figure 23. FWD back-calculated modulus of asphalt layers (left). Back-calculated asphalt modulus vs temperature (right).

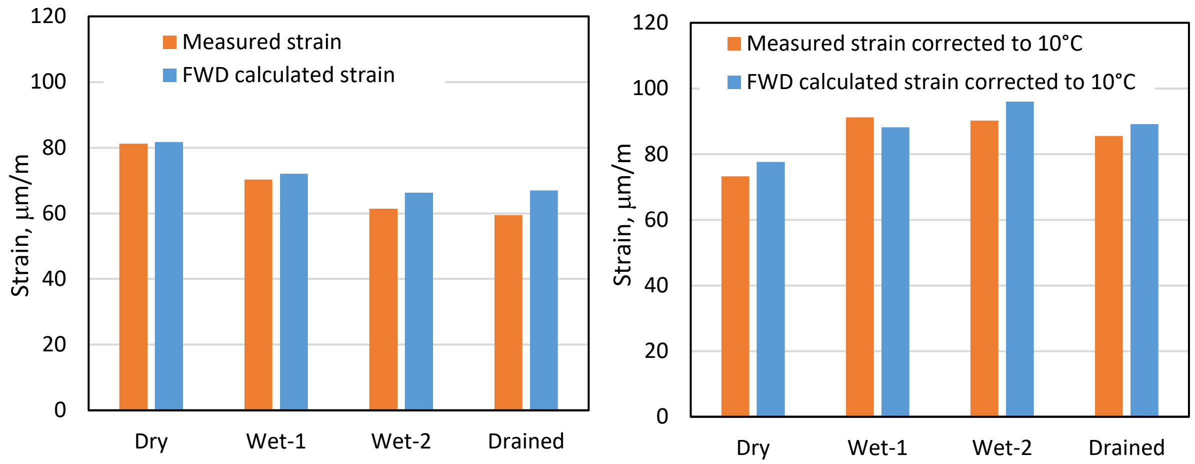

Figure 24. Measured and calculated strains at the bottom of asphalt not corrected to temperature (left). Measured and calculated strains at the bottom of asphalt corrected to temperature of 10 ℃ (right).

4.3.2. GPR velocity measurements

To investigate the best way to discriminate the different groundwater levels, the GPR velocity measurements were determined for depths of 0 to 0.7 m (over the subgrade) and for depth of 0 to 2.7 m (over the whole structure including the subgrade). Figure 25 shows the velocity variation over the depth of 0 to 0.7 m. In this case, the velocity for dry, wet-1 and drained cases produce very similar values of the GPR velocity. This is because the moisture has not reached or migrated to the depth of 0 to 0.7 m and thus does not affect the velocity. However, for the wet-2 condition, where the groundwater level was in the middle of the subbase layer, the velocity was significantly lower since the moisture reached the depth 0 to 0.7 m. The average velocity for each case is shown in the box plot in Figure 26. It is obvious from the box plots that on average, the dry, wet-1 and the drained conditions showed very similar values of GPR velocity.

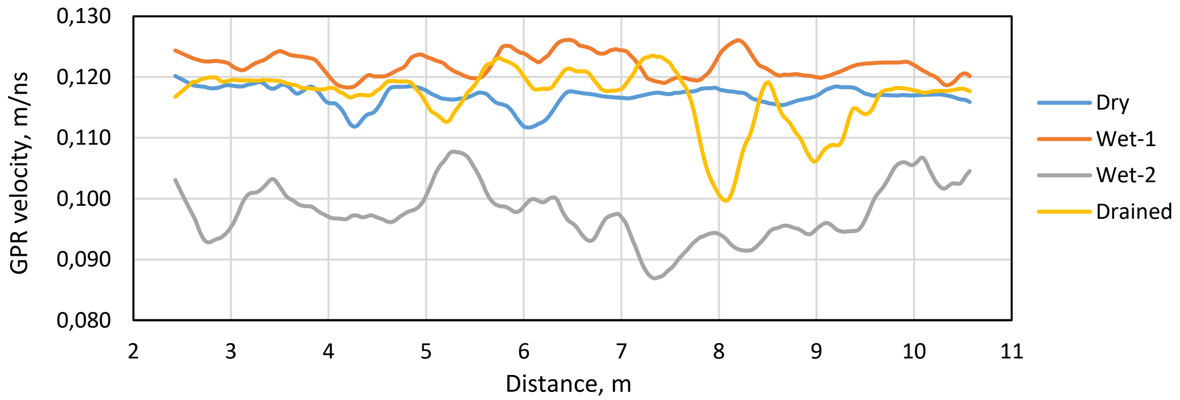

Figure 25.Average GPR Velocity variation in asphalt, base, and subbase layers (0-0.7 m).

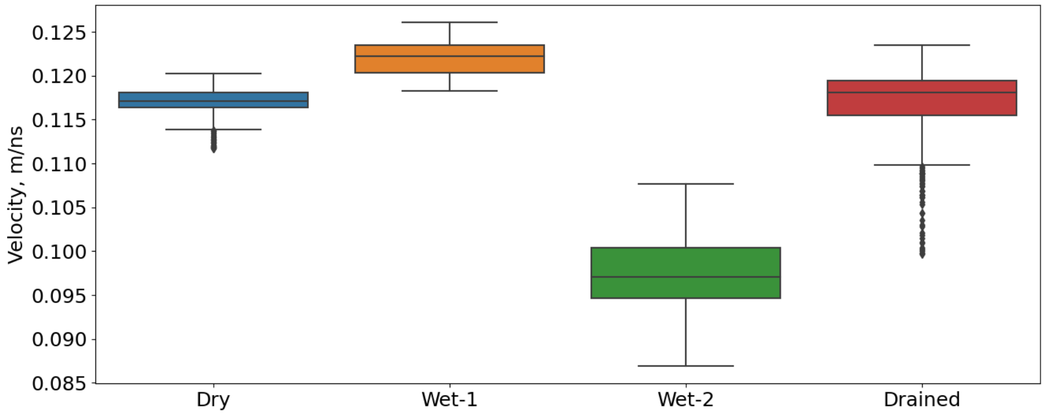

Figure 26. Average GPR velocity over depth 0 to 0.7 m.

The two groundwater levels (wet-1 and wet-2) produced lower velocity for the depth 0 to 2.7 m compared to the dry and the drained conditions. In this case, the velocity for the wet-2 (groundwater level in the middle of the subbase) condition was relatively lower than the velocity at the wet-1 condition where the groundwater level was below the top of the subgrade. Figure 27 shows the velocity variation along the length of pavement. The box plots showing the distributions of the velocities are shown in Figure 28. The dry and drained condition produced very similar values as indicated in the figures.

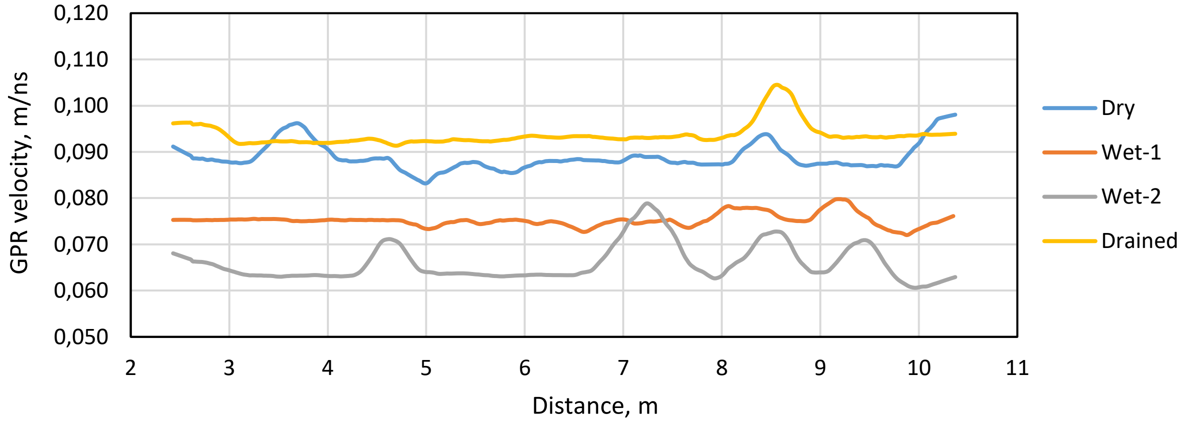

Figure 27. Average GPR Velocity variation in asphalt, base, subbase, and subgrade layers (0-2.7 m).

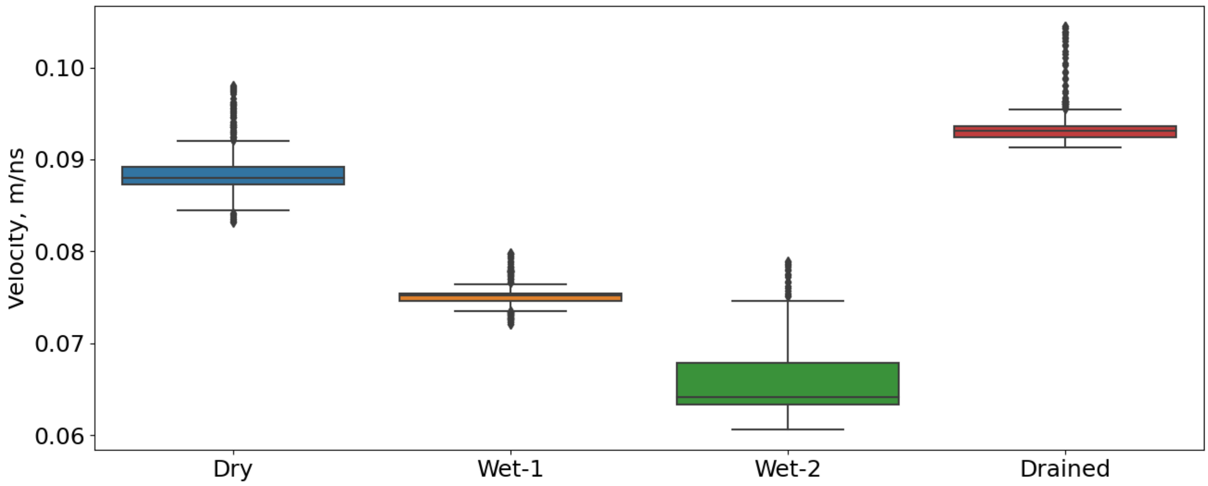

Figure 28. Average GPR velocity over depth of 0 to 2.7 m.

4.4. Discussion

As indicated by the results of this work, for all the cases presented, the measured FWD deflections and the derived indices agreed very well with the GPR velocity measurements with regards to the moisture levels. Increasing the groundwater level increased the FWD deflections and reduced the GPR velocity. Thus, the results of this work verified previous works (Arnold et al. (2017)) that the method could be used to discriminate road sections with different moisture conditions. However, the method did not provide the actual volumetric or gravimetric moisture content, rather it identified the relative water content based on the variations of the GPR velocity. This was clearly demonstrated by the measurements at the indoor full-scale facility. An empirical model relating the moisture content with the apparent dielectric constant could be used to estimate the actual water content (Topp et al., 1980; Di Zhang, 2012).

The FWD deflection at sensor location D1200 was used to indicate the presence of moisture in the studied test structures. The strain at the bottom of the asphalt layers was also evaluated to investigate its sensitivity to increased groundwater levels. As shown in the results, the TDOK 2019:0463 model produced results that are in a very good agreement with the measured strains as shown in the measurements at the indoor full-scale facility. In general, the strain increased as the groundwater level increased.

Using the FWD or the Traffic Speed Deflectometer (TSD) measurements with GPR to assess structural condition of pavements would facilitate the interpretation of the collected FWD/TSD data. Furthermore, a 500 MHz antenna was used in this project. This was selected to penetrate deeper into the pavement structure. Therefore, combining the FWD/TSD or other automatic road monitoring techniques with GPR having a high and low frequency antenna would provide layer thickness information, and state of moisture conditions, respectively, that would enhance the quality of the collected road performance data.

5. Conclusions and Recommendations

GPR and FWD measurements under dry and wet conditions have been conducted on pavement structures both in field and indoor test facilities. The ground water level of the test objects was varied by either closing the drainage facilities or by adding more water to the pavement system. A GPR configuration having two receivers each 500 MHz antennas was employed for collecting the data.

An apparent correlation was found between the FWD and GPR measurements. The TDOK 2019:0463 model was used to estimate the tensile strain at the bottom of the asphalt layers from the FWD measurements. The strains revealed the impact of increased moisture level in the unbound layer on the asphalt layer. Furthermore, the FWD tests at the indoor facility indicated that, the TDOK 2019:0463 model prediction agrees very well with the measured strain at all test temperature and moisture conditions.

In this work only the average GPR velocity was evaluated as an indicator for the presence of moisture in the pavement. Therefore, it is recommended to investigate other GPR parameters such as frequency or the amplitude of the GPR signal which might have better correlation with moisture content. Additionally, this study was limited to correlating the GPR velocity with the FWD deflection measurements at different moisture conditions. This is due to the fact that none of the studied section were installed with moisture sensors. Achieving this may require GPR measurements at field or test road sections equipped with moisture sensors.

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