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# Impact of temperature and moisture on the tensile strain of asphalt concrete layers

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**ABSTRACT**

Moisture in unbound layers and temperature in asphalt layers affect the structural response of pavements, such as the tensile strain at the bottom of asphalt concrete layers. Previous studies have proposed relationships for estimating tensile strain at the bottom of an asphalt layer from Falling Weight Deflectometer (FWD) surface deflection measurements. These relationships have been developed based on theoretical calculations of strains and surface deflections. The main objective of this study was to evaluate these relationships using measured FWD deflections and tensile strains at the bottom of asphalt concrete layers. Three instrumented test structures were considered in the study. FWD and strain measurements were conducted at varying groundwater levels in the subgrade and temperatures in the asphalt concrete layers. The results revealed that the relationships have poor agreement with measured strains. A new relationship is proposed that incorporates the volumetric water content in the subgrade and the temperature in the asphalt layers in addition to the surface FWD deflections.

## 1. Introduction

Condition assessment of pavement plays a major role in maintenance and rehabilitation strategies for many state highway agencies (Khattak *et al.* 2012). The Falling Weight Deflectometer (FWD) is a deflection-testing device commonly used for condition assessment of pavements. Since the FWD is easy to use and simulates traffic loading quite well, it is used by many agencies to evaluate the structural capacity of a pavement (Huang 1993, Doré and Zubeck 2009). The deflections obtained from FWD measurements may be used to estimate stresses and strains induced in a structure by wheel load (ECDGT 1997, Park and Kim 2003). FWD tests are frequently performed to calculate strains at the bottom surface of the asphalt layer in order to determine the fatigue life of the pavement with respect to bottom-up cracking (Park and Kim 2003).

The major factors that influence deflections derived from FWD testing are pavement conditions, loading, pavement structure and environmental conditions (Huang 1993, ECDGT 1998). For flexible pavements, deflections obtained in areas with cracking and rutting deterioration are normally higher than those in areas free of distress (Huang 1993). The most frequent load used with FWD is 50 kN, which corresponds to a standard axle load of 100 kN (ECDGT 1997). Incorrect layer thicknesses in the analysis of deflection measurements therefore result in incorrect moduli and strain at the bottom of asphalt concrete (AC) layers (Jansson 1994, Ullidtz 1998). The temperature of the AC layers and the water content of the base and subgrade are two of the most important environmental factors that influence flexible pavement performance (Zuo *et al.* 2007, Qiao *et al.* 2013).

The stiffness and fatigue characteristics of bituminous layers are sensitive to moisture intrusion and temperature changes.

The combined effect of traffic loading and moisture, as in the case of traffic loading on wet pavement, leads to a reduction in dynamic modulus (Dhakal and Ashtiani 2016, Sulejmani *et al.* 2019). A change in the AC temperature directly affects the stiffness of the bound layers, which changes the stress state throughout the pavement. This change in stress state can, in turn, affect the performance of the underlying unbound layers, since they normally exhibit stress dependence (Zuo *et al.* 2007). Asphalt softens at higher temperatures and thus is more prone to higher horizontal strains at the bottom of the asphalt layers (Huang 1993, Lukanen *et al.* 2000, Marshall *et al.* 2001, Losa *et al.* 2008, El-Maaty 2017). In practice, when pavement performance is periodically controlled or when comparisons between pavement structures are made, the Swedish Transport Administration (2012b) recommends performing FWD measurements during autumn, when temperatures are around 10°C and the unbound layers and subgrade are usually free from water.

Likewise, moisture content changes in the base and subgrade soils affect the stiffness of those pavement system components (Zuo *et al.* 2007, Erlingsson 2010). Excess moisture content reduces the resilient modulus of the unbound layers, causing increased strains in the AC layers through poorer support to the asphalt bound layers (Roberts *et al.* 1996; Said *et al.* 2011, Salour and Erlingsson 2014). This strain is an important factor in cold regions, where pavements commonly become saturated during the spring thaw, and the stiffness modulus in the granular layers decreases (Huang 1993, Salour and Erlingsson 2012, 2013). Tests performed by Salour and Erlingsson (2014) revealed that the estimated strain at the bottom of the AC layer increased by 34% when the groundwater table (GWT) level was raised from 2.5 to 1.0 m below the road surface. Similarly, Saevarsdottir and Erlingsson (2013) showed that measured tensile strain at the

bottom of the bituminous base significantly increased when the GWT rose from a considerable depth to 30 cm below the sub-grade surface. Differences in the underground water table are usually not controlled when FWD measurements are performed, which causes variation in the results.

Tensile strain at the bottom of the bituminous layer is usually defined as critical for evaluating fatigue cracking. The tensile strain of an asphalt pavement is traditionally estimated using the back-calculated modulus from FWD measurements. Relationships for estimating tensile strains directly from FWD surface deflections have also been previously developed (Jansson 1994, Xu et al. 2002). These relationships assume that the effects of environmental conditions are reflected in the deflections from the FWD measurements. Temperature and moisture content parameters are, therefore, not directly included in these relationships. Moreover, these relationships have been developed based on theoretical calculations of surface deflections and horizontal strain at the bottom of the asphalt layer using multilayer elastic theory (Jansson 1994, Xu et al. 2002).

This study aimed to develop new relationships for predicting tensile strain with regard to variations in temperature and groundwater levels in pavement structure using deflections from FWD measurements. The FWD measurements were performed on three different full-scale indoor test structures. The structures were instrumented to measure the strain at the bottom of the bituminous layer, the temperature in the AC layer and the volumetric water content in the subgrade.

## 2. Pavement structures and laboratory tests

### 2.1. Test structures and instrumentation

Three indoor pavement structures were built at VTI (The Swedish National Road and Transport Research Institute) to study the effects of moisture and temperature on the structural

**Table 1.** Material, binder type, binder content and air void content for all bound layers (Arvidsson 2014).

| Structure | Asphalt concrete | Binder type | Binder content [weight–%] | Air void [%] |
|---|---|---|---|---|
| SE 14 | ABT 16 | 70/100 | 6.4 | 2.5 |
| | AG 32 | 160/220 | 4.1 | 4.5 |
| SE 18 | ABT 16 | 70/100 | 5.8 | 2.5 |
| | AG 22 | 160/220 | 4.2 | 4.5 |
| SE 20 | ABT 16 | 70/100 | 6.3 | 2.5 |

responses of the pavement structure to loading. The temperature, volumetric moisture content of the pavement and horizontal strain at the bottom of the AC layers were monitored using instrumentation (Arvidsson 2014).

Three flexible pavement structures frequently used in Sweden were studied. The structures are denoted as SE 14, SE 18 and SE 20 and are shown in Figure 1. The wearing course for all pavement structures was made of dense asphalt mixture, denoted ABT16 70/100. SE 14 was the thickest structure, with a total of 625 mm of pavement structure, including 111 mm of AC layers. The structure consisted of a 79 mm AC base course, denoted AG32 160/220. SE 18 was the 'medium' structure, having 101 mm thick asphalt layers. It consisted of 53 mm of road base mix, denoted AG22 160/200. Pavement SE 20 was the thinnest structure, having a wearing course of ABT16 70/100. The bituminous structures consisted of only 70 mm of wearing course ABT 16 70/100 and 240 mm of unbound layers (see Figure 1). The asphalt mixtures were produced with granite aggregate.

Table 1 describes the materials used for the bound layers. Table 2 shows the types of unbound materials, the second deformation modulus (Ev2) and the ratio of first and second deformation moduli (Ev2/Ev1) from the plate loading test conducted on the unbound layers. Figure 2 shows the grain size distributions of the five asphalt mixes.



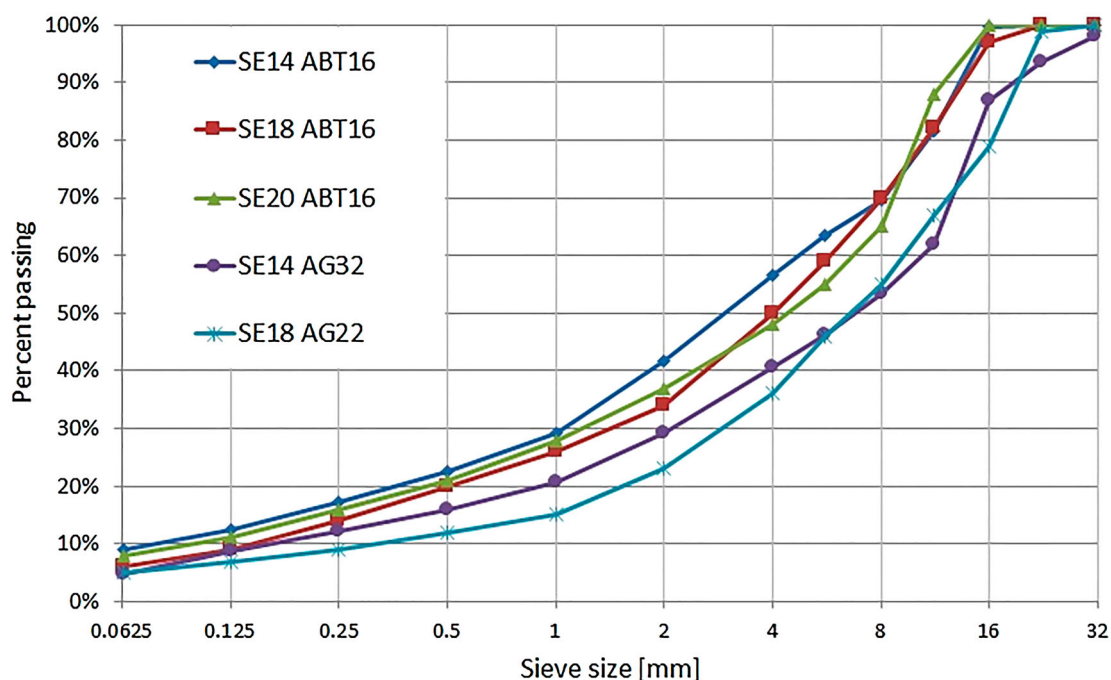**Figure 1.** Cross-sections of pavement structures SE 14, SE 18 and SE 20 and the vertical location of the instrumentation.
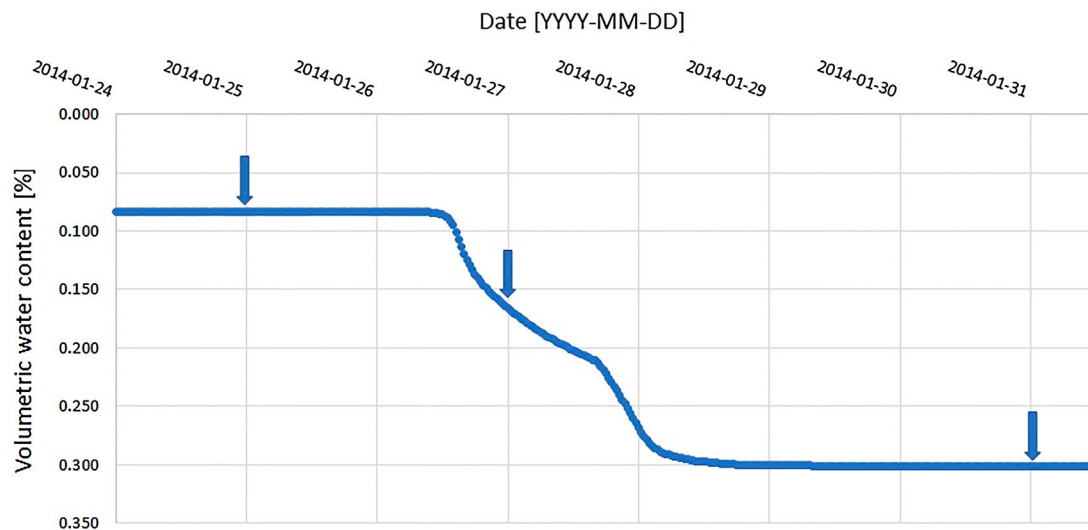
**Figure 2.** Gradation curves for asphalt mix types ABT 16, AG 22 and AG 32 (Arvidsson 2014).

**Table 2.** Types of unbound materials and results of plate loading test subgrade (Ev2 and Ev2/Ev1) (Arvidsson 2014).

| Structure | Layer | Material | Ev2 [MPa] | Ev2/Ev1 |
|---|---|---|---|---|
| **SE 14** | Base course | Crushed stone [0/32] | 156 ± 12.14 | 1.9 ± 0.14 |
| | Sub-base | Crushed stone [0/90] | – | – |
| | Subgrade | Silty sand | 63 ± 3.23 | 2.7 ± 0.23 |
| **SE 18** | Base course | Crushed stone [0/32] | 105 ± 8.14 | 2.5 ± 0.34 |
| | Sub-base | Crushed gravel [0/90] | – | – |
| | Subgrade | Silty sand | 43 ± 3.94 | 3.0 ± 0.24 |
| **SE 20** | Base course | Crushed stone [0/32] | 74 ± 3.04 | 2.5 ± 0.44 |
| | Sub-base | Crushed gravel [0/90] | | |
| | Subgrade | Silty sand | 48 ± 0.34 | 3.1 ± 0.14 |

The tests were conducted in an indoor full-scale pavement test facility where pavements can be constructed with an ordinary road construction machine. The size of the test pits was 3 m in depth, 5 m in width and 15 m in length. The test pits were filled with silty sand to a thickness of 2.5 m to act as a subgrade for the test structures. The facility had a heating/cooling system, and temperatures could thus be held constant.

A schematic overview of the instruments used in this study is shown in Figure 1. The instrumentation consisted of the following (Wiman 2006, Arvidsson 2014):

- Moisture content sensors to measure the volumetric water content at 22.5 cm below the subgrade surface (water content reflectometers);
- Asphalt strain gauges (ASGs) to measure the horizontal strain at the bottom of the asphalt bound layers in the longitudinal and transverse directions (H-shaped gauges from Dynatest); and
- Temperature sensors in the AC layer (temperature gauges).

## 2.2. Test programme

The structural response of the pavement was evaluated by conducting FWD tests. In SE 14, the level of the GWT was chosen to simulate three conditions as follows: (1) natural moisture – simulates a standard situation where the GWT is at a considerable depth, with no lateral moisture transfer and very limited evaporation; (2) moderate moisture – simulates well-functioning trenches where the GWT level is below the trench bottom, which was based on Swedish regulations stating that it should be at least 30 cm below the subgrade surface; and (3) heavy moisture – simulates the severe case when water is running in the trenches and the GWT lies just below the subgrade surface, according to Table 3. SE 18 and SE 20 were tested only at different temperatures. The chosen temperatures were within the range of normal temperatures used in the Swedish Mechanistic Empirical (ME) Program for pavement design representing spring, autumn and summer in Sweden (Swedish Transport Administration 2011).

The FWD measurements were performed using a 50 kN load level, corresponding to a standard axle load of 100 kN. Seven geophones were used to measure vertical deflection. The geophones were located at 0, 200, 300, 450, 600, 900 and 1,200 mm from the centre of the load plate. Table 3 summarises the different environmental conditions for the measurements performed. The measurements were performed when the target temperature and GWT was stabilised according to the temperature and moisture sensors in the pavement. Figure 3 shows the volumetric water content.

## 3. Results

### 3.1. FWD and horizontal strain measurements

The following section shows the FWD deflection measurements and measured horizontal strains at the bottom of the
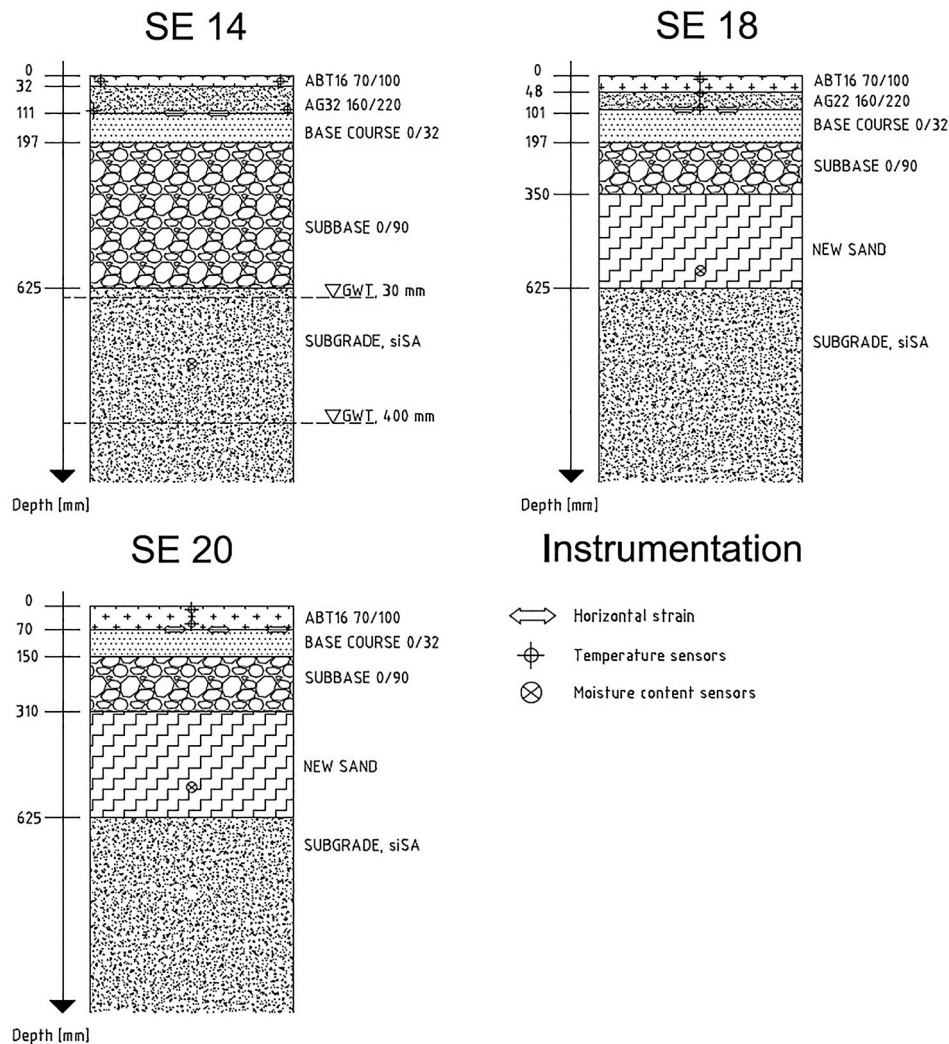
**Table 3.** Temperature and groundwater levels used in the study.

| Environmental Conditions | SE 14 | | | | | SE 18 | | | SE 20 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature [°C] | 5.5 | 9.0 | 18.5 | 10.8 | 11.3 | 4.9 | 10.3 | 17.4 | 0.9 | 6.6 |
| GWT (below subgrade surface) [mm] | >3000 | >3000 | >3000 | 400 | 30 | >3000 | >3000 | >3000 | >3000 | >3000 |
| Volumetric water content (22.5 cm below subgrade surface) [%] | 8.2 | 8.3 | 8.3 | 20.9 | 30.1 | 16.6 | 16.1 | 16.0 | 8.0 | 8.0 |

## SE 14



## SE 18



## SE 20



## Instrumentation



Horizontal strain

Temperature sensors

Moisture content sensors

**Figure 3.** Volumetric water content measurements for SE 14 showing test dates (arrows).

asphalt bound layers. It should be noted that the deflections and measured strains presented in Figures 4–7 are the mean values from two location measurements for structures SE 14 and SE 18 and three measurements for SE 20.

### 3.1.1. SE 18 – effect of temperature
Figure 4(a) illustrates the mean of vertical deflections at different pavement temperatures (4.9°C, 10.2°C and 17.4°C). The effect of temperature clearly decreased with horizontal distance from the loading centre, especially after a distance of 300 mm, which indicates that temperature influences the AC layers (Doré and Zubeck 2009). Figure 4(b) shows the mean of measured horizontal strains, indicating that strain increases as temperature increases.

Surface deflection and measured horizontal strain increased as pavement temperature increased. Similar results have been presented by El-Maaty (2017). A change in temperature from 10°C to 18°C increased vertical deflection by 12% and measured strain by 15% at the loading centre.

### 3.1.2. SE 20 – effect of temperature on thin asphalt layers
The FWD measurements were performed at different temperatures in order to determine the relationships between tensile strain and temperature for a thin asphalt pavement structure such as SE 20 (1°C–27°C). The AC thickness for this structure was only 70 mm. Asphalt thickness thinner than 75 mm is not recommended for estimating the strain at the bottom of the asphalt layer according to the Swedish standard (Jansson 1994). Figure 5 illustrates the vertical deflection and measured horizontal strains for structure SE 20 to clarify the influence of temperature changes on structures with a thin AC layer.

Figure 5(a) shows that the vertical deflection at the loading centre increased from 676 to 716 μm when the temperature increased from 0.9°C to 6.6°C. The tensile strain at the bottom of the asphalt layer also increased slightly from 353 to 364 μm/m (Figure 5(b)). However, at temperatures higher than 6.6°C, the tensile strains unexpectedly decreased as the temperature increased. Further, the deflection basin from structure SE 20 showed that at temperatures higher than 6.6°C, the surface deflection at the loading centre remained nearly stable or decreased slightly as temperature increased. This finding might be explained by the fact that the combined effect of an increase in temperature and thin AC thickness changes the response of the asphalt layer from acting as a beam to a membrane deformation pattern, which results in lower tension (Papadopoulos and Santamarina 2016, 2019). Measurements
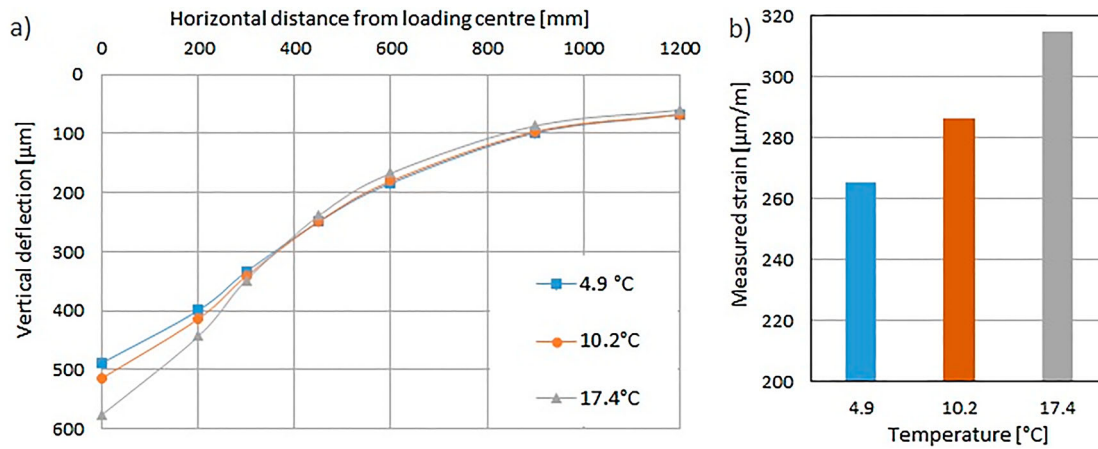
**Figure 4.** (a) FWD measurements, (b) measured horizontal strain at the bottom of the asphalt bound layers for structure SE 18.
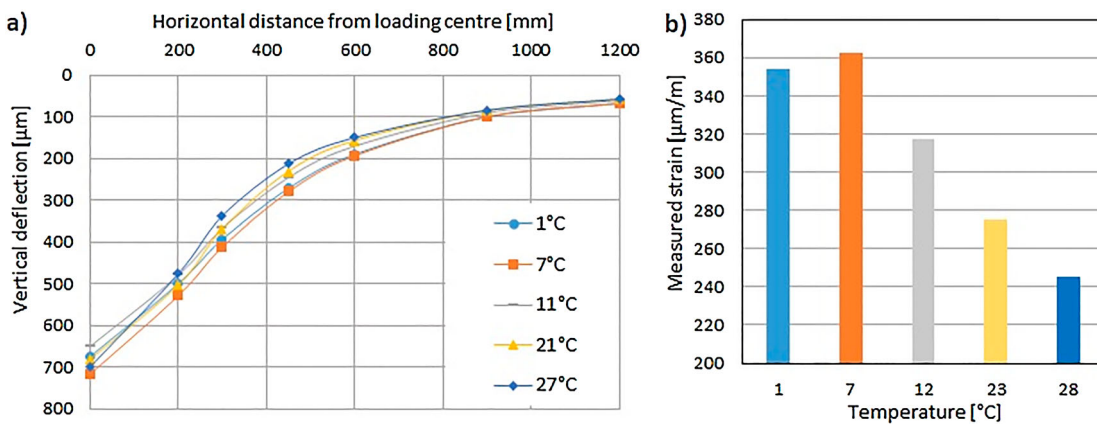


**Figure 5.** (a) FWD measurements, (b) measured horizontal strain at the bottom of the asphalt bound layers for structure SE 20.

for SE 20 higher than 6.6°C are therefore not included in further analysis of the results.

### 3.1.3. SE 14 – effect of temperature and groundwater level
Figure 6 presents the vertical deflections and measured horizontal strains at different temperatures and natural moisture content of the structure. Measurements at 5.5°C were performed three months earlier than the other measurements for the same structure.

Figure 6 shows that vertical deflections and horizontal strain measurements were greater at 5.5°C than 9°C. Additionally, the deflection basin for 5.5°C did not converge with the other basins after 300 mm, meaning that there are factors in addition to temperature affecting the measurements at 5.5°C, which is unreasonable. These measurements were performed three months earlier, as noted above. Therefore, some unknown changes in the test conditions might have occurred during these three months (e.g. aging).

At approximately 10°C, two additional FWD tests were conducted with GWT levels at 3 and 40 cm below the subgrade surface (see Figure 7(a)) to illustrate the effect when the GWT is raised. Figure 7(b) shows the horizontal strain for the conducted measurements at approximately 10°C with varying groundwater levels.

Figure 7 shows that the deflection basin and measured tensile strains increased considerably as the GWT level was raised. Changes in GWT level and subsurface moisture conditions significantly affected the outer part of the deflection basin, which indicates that the subgrade weakened (Doré and Zubeck 2009). Moreover, changes in the groundwater level from a considerable depth to 3 cm below the subgrade surface increased vertical deflection by 43% and measured strains by 18% at the loading centre. Similar findings have been reported in a previous study (Salour and Erlingsson 2014).

### 3.2. Estimation of strain

Relationships for estimating strains at the bottom of the bituminous layers from FWD measurements have been previously reported (Jansson 1994, Kim 2001, Xu et al. 2002, Xu et al. 2003). Equation (1) is based on multiple linear regressions to calculate strains at the bottom of bituminous layers according to the Swedish Transport Administration (2012a) for several different pavements with asphalt layer thicknesses greater than 75 mm.

$$\varepsilon = 37.4 + 0.988*D_0 - 0.553*D_{300} - 0.502*D_{600}, \qquad (1)$$

where $\varepsilon$ is the tensile strain at the bottom of a bituminous layer [µm/m] and $D_0$, $D_{300}$ and $D_{600}$ are deflections [in µm] at 0, 300 and 600 mm, respectively, from the centre of the loading plate.
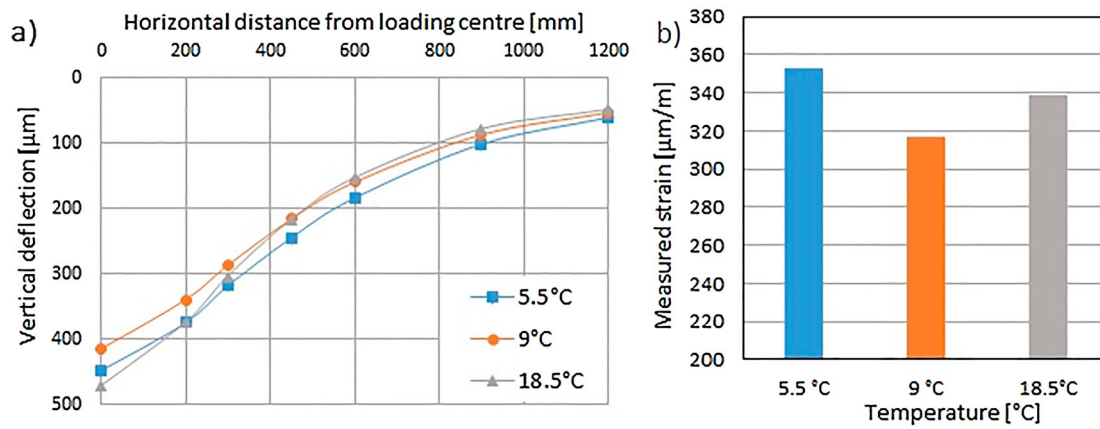
**Figure 6.** (a) FWD measurements, (b) measured horizontal strain at the bottom of the asphalt bound layers for structure SE 14.
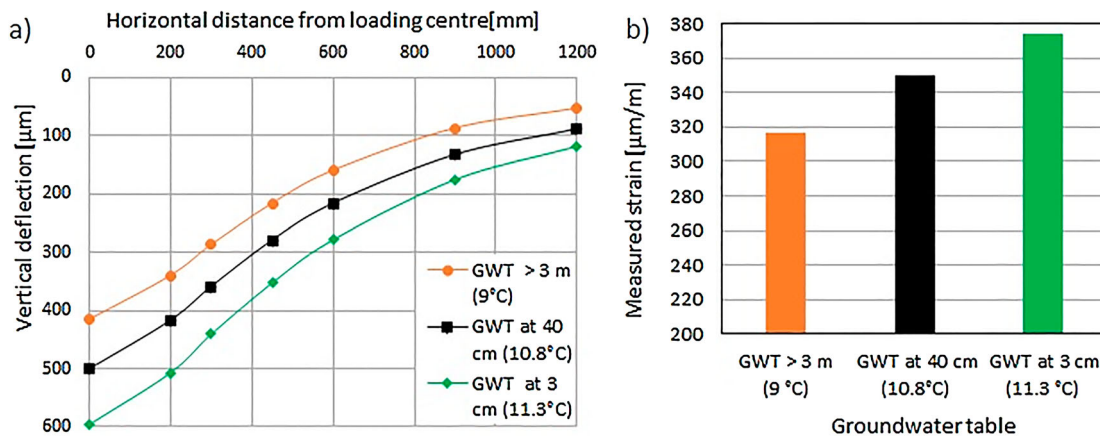


**Figure 7.** (a) FWD measurements at 10°C with varying groundwater levels, (b) measured horizontal strain at the bottom of the asphalt bound layers for structure SE 14.

The tensile strain at the bottom of the bituminous layer can also be estimated using formulas developed by the Asphalt Layer Condition Assessment Program (APLCAP) (Kim 2001, Xu et al. 2003). Equation (2) is proposed for aggregate base pavements with AC, $H_{ac}$ < 6 in (150 mm):

$$Log(\varepsilon_{ac}) = 0.7798*\log{(SCI)} + 0.2279*\log{(BDI)}$$
$$+ 0.5736*\log{(H_{ac})} + 0.0410*H_{ac} + 1.1604 \quad (2)$$

where SCI and BDI are deflection basin indicators [in mil] and $H_{ac}$ is the thickness of the asphalt layer [in in].

Equations (1) and (2) were developed based on theoretical calculations of surface deflections and horizontal strain at the bottom of the AC layer using multilayer elastic theory. These relationships assume that the effects of environmental conditions are reflected in the deflections from the FWD measurements. AC layer thickness is included in Equation (2) but not in Equation (1). Neither temperature nor moisture content parameters are directly included in these relationships. Figure 8 compares estimated strains using Equations (1) and (2) with measured strains.

Figure 8(a) shows that the coefficient of determination ($R^2$) for the estimated and measured strains was determined to be 0.18 using Equation (1) (Swedish formula). Figure 8(b) shows that the $R^2$ using Equation (2) was 0.52 (APLCAP formula) for the

data measured in this work. The low $R^2$ values indicate poor fit with the measured strains. Figure 8(a and b) illustrate that structure SE 18 with its 100 mm thick AC layer, natural moisture content in the subgrade and temperatures ranging between 5°C and 18°C shows the best agreement between the estimated and measured strains for both Equations (1) and (2). However, for structure SE 20, with its thin hot mix asphalt (HMA) layer (70 mm) (measurements at temperatures >7°C were not included) and at conditions with excess moisture content in the subgrade, the fit between the estimated and measured strains was poorer.

### 3.3. Regression analysis

Multiple linear regression analysis was performed between the measured asphalt strain (dependent variable) and deflections. Asphalt layer thickness, temperature in the asphalt mixture and moisture content at 22.5 cm below the subgrade surface were tested as independent variables. The thickness of the AC layer was shown not to be significant and is therefore not included in the statistical analysis below. Table 4 shows the ANOVA analysis.

Since, in practice, no moisture content information is available for a pavement due to difficulties in measurement, an additional multiple linear regression analysis was performed without the volume of water content in the pavement. That ANOVA analysis is shown in Table 5.

**Table 4.** ANOVA analysis with moisture content as an independent variable.

| Statistic | Coefficient | Standard Error | P-value |
|---|---|---|---|
| Constant | 199.25 | 57.01 | 3.E-03 |
| Temperature | 5.31 | 1.10 | 2.E-04 |
| Moisture content | −5.50 | 1.50 | 2.E-03 |
| D0 | 0.69 | 0.28 | 3.E-02 |
| D300 | −1.62 | 0.75 | 5.E-02 |
| D900 | 3.39 | 0.73 | 3.E-04 |
| $R^2$ | 0.76 | n/a | n/a |
| Adjusted $R^2$ | 0.68 | n/a | n/a |
| Standard Deviation | 20.97 | n/a | n/a |

*n/a = not applicable.

**Table 5.** ANOVA analysis without moisture content as an independent variable.

| Statistic | Coefficient | Standard Error | P-value |
|---|---|---|---|
| Constant | 298.08 | 66.24 | 3.E-04 |
| Temperature | 3.05 | 1.19 | 2.E-02 |
| D0 | 1.03 | 0.35 | 9.E-03 |
| D300 | −2.43 | 0.94 | 2.E-02 |
| D900 | 2.89 | 0.95 | 7.E-03 |
| $R^2$ | 0.55 | n/a | n/a |
| Adjusted $R^2$ | 0.44 | n/a | n/a |
| Standard Deviation | 27.62 | n/a | n/a |

*n/a = not applicable.

The values of $R^2$ with and without water content are 0.76 (Table 4) and 0.55 (Table 5), respectively. The P-values of the coefficients in Tables 4 and 5 show that all independent variables significantly affected the estimation of strain at the bottom of the AC layer. Table 5 shows that without considering moisture content, the $R^2$ value decreased from 0.76 to 0.55, which indicates that moisture content plays a major role in estimating the strain at the bottom of the AC layer.

The two relationships developed to determine the strain at the bottom of the AC layer based on Tables 4 and 5 are shown in Equations (3) and (4), respectively.

$$\varepsilon_{ac} = 199.25 + 5.31*T - 5.50*v + 0.69*D_0$$
$$- 1.62*D_{300} + 3.39*D_{900} \tag{3}$$

$$\varepsilon_{ac} = 298.01 + 3.05*T + 1.03*D_0 - 2.43*D_{300}$$
$$+ 2.87*D_{900}, \tag{4}$$

where $\varepsilon_{ac}$ is tensile strain at the bottom of the asphalt mixture [μm/m], $T$ is the temperature (°C), $v$ is the volume of water

content at 22.5 cm below the subgrade surface [%] and $D_0$, $D_{300}$ and $D_{900}$ are the deflections at horizontal distances from loads of 0, 300 and 900 mm [in μm], respectively. The estimated strains using Equations (3) and (4) were compared to the measured strains (see Figure 9).

As can be seen from Figure 9(a), Equation (3) shows better agreement with the predicted and measured strains at the bottom of the AC layers compared to Equations (1) and (2). Equations (1) and (2) were developed based on theoretical calculations of surface deflections and horizontal strain at the bottom of the asphalt layer simulating pavements that cover the range of layer thickness and stiffness modulus for many existing pavements. It is understood that Equations (1) and (2) were developed under the assumption that the effects of environmental conditions are reflected in the deflections, which may explain why Equations (1) and (2) have a lower determination coefficient than Equation (3) when the range of temperature and groundwater level is included. Considering the difficulty of measuring water content under actual field conditions, Equation (4) was developed without moisture content as an independent variable, although it shows low $R^2$. Temperature is directly included in Equation (4), and it shows a slightly higher $R^2$ value than Equations (1) and (2). However, Equation (4) has a considerably lower $R^2$ value than Equation (3), which indicates the significant contribution of water content in explaining the strain at the bottom of the AC layer. Thus, the results of this study show that environmental conditions should be directly included when the tensile strain is estimated in order to correctly estimate the tensile strain from the measured FWD deflections.

## 4. Discussion

This study revealed that temperature mainly affects FWD deflections from the loading centre to a distance of 300 mm, which agrees with an earlier study by El-Maaty (2017). Temperature was also found to significantly influence the measured horizontal strain at the bottom of asphalt layers. Earlier studies (Papadopoulos and Santamarina 2016, 2019) have shown that the combined effect of high temperature and thin AC thickness changes the response of the asphalt layer from acting as a beam to a membrane deformation pattern, which results in lower
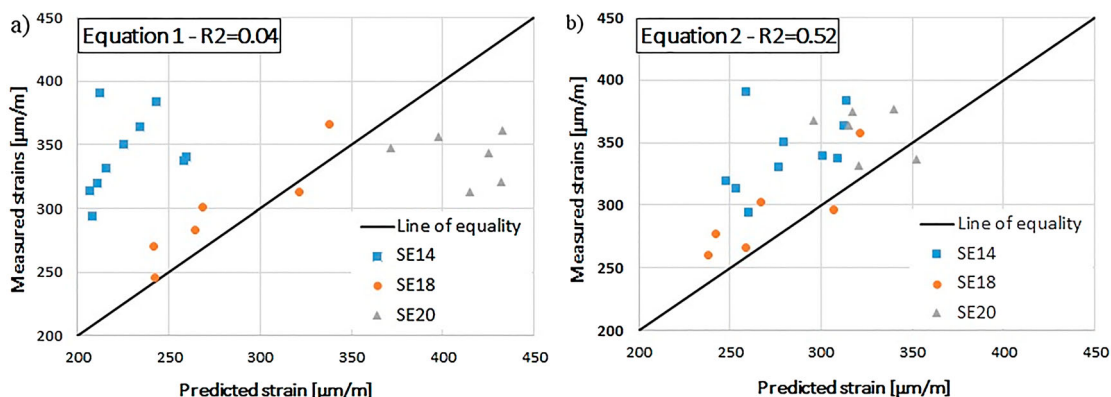


**Figure 8.** (a) Measured and predicted values of horizontal strain at the bottom of the asphalt layer using Equation (1) and (b) Equation (2) with respect to the 45° equality line.
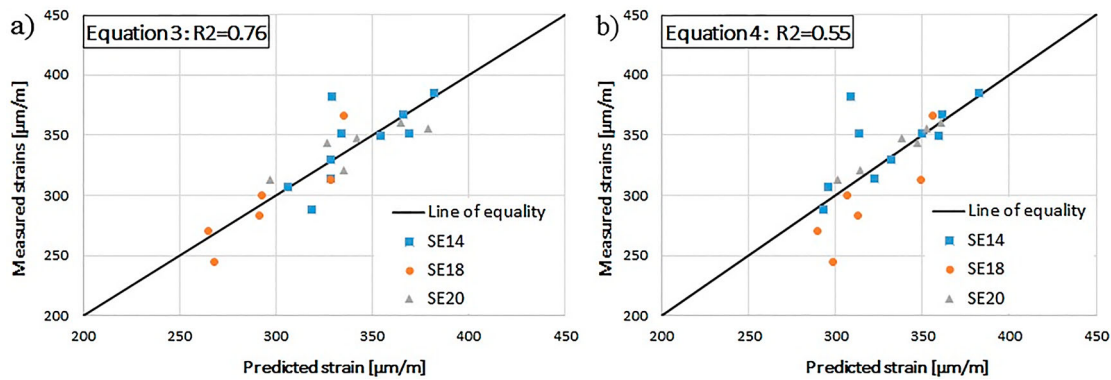
**Figure 9.** Measured and predicted values of horizontal strain at the bottom of the asphalt layer using (a) Equation (3) and (b) Equation (4) with respect to the 45° equality line.

tensile strain at the bottom of the AC layer. For structures with a thin AC layer (SE 20) and FWD measurements at high temperatures (> 6.6°C), centre deflection and measured deflections and strains were almost the same or decreased as temperature increased. These results are consistent with the recommendations from the Swedish standard that tensile strain at the bottom of an AC layer should not be directly predicted with Equation (1) for structures with AC layers thinner than 75 mm.

The presence of moisture in the subgrade significantly affected the horizontal strain at the bottom of the AC layers under load from FWD. For structure SE 14, the rise in groundwater level from considerable depth to 30 cm below the subgrade surface had a greater impact on the measured horizontal strain and vertical deflection than increasing the temperature of the asphalt layer from 9°C to 18.5°C. The collected data showed a correlation between the water content and the measured strain at the bottom of the AC layer. Similar findings have been reported in other studies (see, e.g. Salour and Erlingsson 2013, Saevarsdottir and Erlingsson 2014). Increased moisture content in the unbound layers and subgrade may cause increased strains in the AC layers through poorer support to asphalt bound layers (Roberts *et al.* 1996, Said *et al.* 2011).

This study showed that the strains estimated using the relationships represented by Equations (1) and (2) have poor agreement with measured strains for structures, particularly under conditions with excess moisture content in the subgrade. A new relationship, Equation (3), was developed to estimate the horizontal strain at the bottom of an AC layer based on measured FWD deflections, strains, temperatures and moisture content. An ANOVA analysis showed that all independent variables selected in this equation have a significant effect on the predicted strain at the bottom of the AC layer. As noted earlier, AC layer thickness is an important factor when the strain at the bottom of the AC layer is predicted (Jansson 1994, Ullidtz 1998, Said *et al.* 2011). However, a multiple linear regression analysis showed the thickness of the AC layer was not a significant factor ($p = 0.15$) in estimating the strain at the bottom of the AC layer. This finding may be because of the relatively narrow range of AC layer thicknesses (70–110 mm) for the structures used in this study, which are within the range of typical Swedish structures (Said *et al.* 2011).

The relationship represented by Equation (3) that includes moisture content as an independent variable showed better accuracy with measured strains compared to the relationships represented by Equations (1) and (2). However, Equation (4), which did not include moisture content as a variable, had a considerably lower $R^2$ value compared with Equation (3), indicating the significant influence of moisture content in explaining the strain at the bottom of the AC layer.

The new relationship, Equation (3), offers more flexibility for predicting tensile strain at the bottom of the AC layer with FWD measurements under different temperature and moisture conditions. In practice, this relationship is therefore more flexible for the periodic evaluation of pavement structures. However, more measured data would be useful to verify this relationship. Further studies with a wider range of AC layer thicknesses, temperatures and moisture contents need to be conducted for a better understanding of the impact of these variables on the tensile strain at the bottom of the AC layer. In addition, it would be valuable to study the effect of temperature and moisture based on actual field conditions where the formula in Equation (3) can be validated.

## 5. Conclusions and recommendations

The following conclusions can be drawn from the study:

- Temperature and moisture content make a significant contribution to explaining the strain at the bottom of the AC layer.
- An enhanced relationship develops between temperature, moisture content, surface deflection measurements and the tensile strain at the bottom of the asphalt layer. This relationship can be useful in evaluating the influence of environmental parameters on the strain level at the bottom of the AC layer.
- The adapted relationship represented in Equation (3) can be used to predict strains at the bottom of AC layers even for AC layer thicknesses less than 75 mm but only at temperatures lower than 7°C.
- Validation of the Equation (3) relationship with a wider spectrum of input data would be valuable.

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