Impact of Water on the Structural Performance of Pavements

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ABSTRACT: An accelerated load test has been performed at VTI's test facility in Sweden using a Heavy Vehicle Simulator (HVS). The objective was to investigate the response behaviour and performance of a commonly used flexible pavement structure in Sweden. The instrumented structure was built in a concrete test pit and consists of 10 cm bounded layer, a granular base and a subbase resting on sandy subgrade. The test was divided into three phases: a pre-loading phase, a response phase and the main accelerated loading test where 1,000,000 load cycles were applied. After the preloading phase 500,000 load cycles were applied and then the water table was raised and further 500,000 loading cycles were applied. Raising the groundwater table increased the rate of rutting developed in all unbound layers. From the sensor registrations it is clearly seen that the stiffness of all unbound layers decreased as the water table was raised, thus the pressure cells revealed lower registrations but the vertical strain gauges increased their readings. Further, it was observed that the rate of accumulation of permanent deformation accelerated. This has been interpreted as the impact of higher water content on the characteristics of the unbound layers, the subgrade, subbase and base course.

KEY WORDS: Accelerated pavement testing, heavy vehicle simulator, water content, performance, rutting.

1 INTRODUCTION

An accelerated pavement test (APT), referred to as SE06, using a Heavy Vehicle Simulator (HVS) has been conducted at the Swedish Road and Transport Research Institute (VTI) test facility in Linköping, Sweden. The objective was to investigate the response behaviour and performance of a commonly used pavement structure in Sweden.

The HVS is a linear full-scale accelerated road-testing machine with a heating/cooling system to maintain a constant temperature during testing (Wiman and Erlingsson, 2008). The test was divided into three phases: a pre-loading phase consisting of 20,000 load applications, a response phase to get information on the general response behaviour of the structure due to various axle load and tyre pressures as well as the main accelerated loading test where 1,000,000 load cycles were applied with dual tyre configuration with an axle load of 120 kN and a tyre pressure of 800 kPa. After applying the first 500,000 load cycles the water table was raised and further 500,000 loading cycles were applied. Raising the groundwater table increased the rate of permanent deformation developed in the structure in all unbound layers. The response of the structure and the permanent deformation development was monitored during the test. Therefore it was possible to investigate the influence of the location of the ground water table on the behaviour of the structure.

2 THE PAVEMENT STRUCTURE

The pavement structure was tested in an indoor concrete pit (depth 3 m, width 5 m and length 15 m) under constant environmental conditions (Wiman, 2006). The structure is shown in Figure 1. It consisted of 10.1 cm thick Hot Mix Asphalt, divided into 4.8 cm surface course and 5.3 cm bituminous stabilized base. Underneath, there was a 10.8 cm thick unbound aggregate base over a 14.2 cm thick subbase resting on sandy subgrade (Erlingsson, 2009).

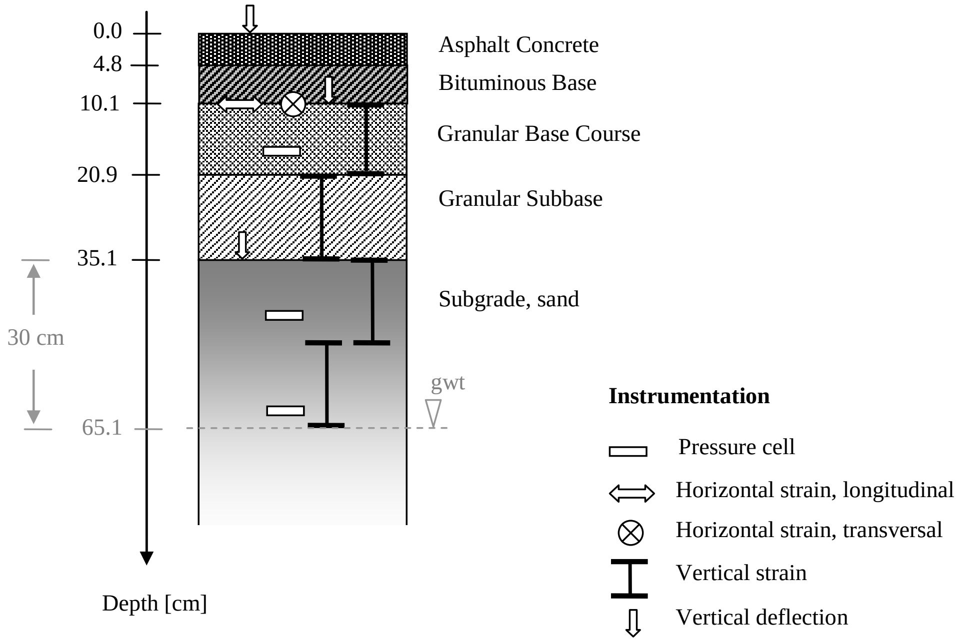

Figure 1: A cross-section of the tested pavement structure along with the vertical location of the instrumentation. The location of the groundwater table, 30 cm below the top of the subgrade, which was introduced after 530,000 repetitions is shown as well.

3 THE APT PROCEDURE

The pavement structure was instrumented to measure its response and performance due to repeated heavy loadings. A schematic overview of the instruments is given in Figure 1. For stresses three sensors were used at each depth, all together nine soil pressure cells (SPC). The tangential strain at the bottom of the bituminous bounded layer was measured with eight asphalt H-bar strain gauges (ASG), four in the longitudinal and four in the transverse directions, respectively. The vertical strain (both elastic and permanent strain) was measured with a total of twelve EMU-coils (inductive coils), three at each depth range. The vertical deflection was measured with linear variable displacement transducers (LVDT's) in relation to the concrete bottom of the test pit.

The HVS test was divided into three steps. The first step was a pre-loading step. Thereafter comprehensive response measurements were carried out and finally an accelerated load test was performed. The pre-loading step consisted of 20,000 passes of a 30 kN single wheel load with a tyre pressure of 700 kPa. In the accelerated testing phase more than 1,000,000 repetitions were applied. The structure was tested for 500,000 load repetitions where the accumulated permanent deformations of the unbound base course, subbase and the upmost 30 cm of the subgrade were monitored as well as the total rut manifested on the surface. Then water was pumped, in a gently manner, into the concrete pit where the structure was located until it rose to the level of 30 cm below the top of the subgrade. This is the same level as the lower plate of the lowest strain sensor in Figure 1. Now additionally and identically 500,000 load repetitions were applied and the accumulated permanent deformation as well as the rutting on the surface was monitored. In addition some response testing was carried out. The performance of the two states where the groundwater table was absent and where it was located at a 30 cm depth below the top of the subbase have both been modelled. They are here referred to as the moist versus the wet state of the structure, respectively.

4 THE RESPONSE BEHAVIOUR OF THE STRUCTURE

The response of the structure was estimated with regular intervals during the main accelerated testing phase. Figure 2 shows the induced vertical stress measured from the pressure cells under the centre of one of the wheels at 15.5 and 60.0 cm depths due to dual tyre loading combination after approximately 250,000 (moist state) and 750,000 (wet state) loading repetitions. Higher registrations are made in the moist state indicating stiffer structure.

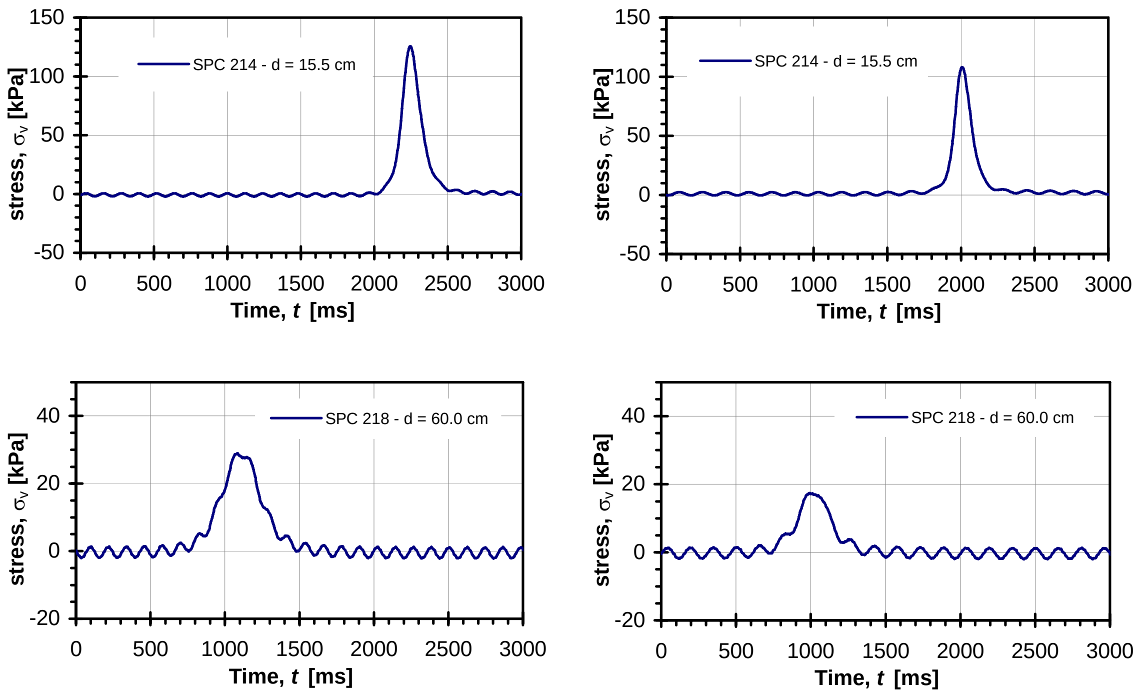

Figure 2: Induced vertical stress registration of two pressure cells sensors located at 15.5 cm and 60.0 cm depths, respectively, during a dual wheel loading conditions from both the moist (left) and the wet (right) phases of the test.

Figure 2 shows the measured vertical stress from the pressure cells under the centre of one of the wheels at the depths 15.6 cm (in the base course) and 60.0 cm (in the subgrade) due to a dual tyre loading combination after approximately 250,000 (moist state) and 750,000 (wet state) loading repetitions. Approximately 30% lower registrations were observed at both depths in the wet state indicating a poorer load spreading properties, thus a softer structure.

Figure 3 shows the induced vertical strain measured from the EMU inductive coils under the centre of one of the wheels over the depth range 10.1 – 20.7 cm and 35.3 – 50.5 cm due to a dual tyre loading combination after approximately 250,000 (moist state) and 750,000 (wet state) loading repetitions. Approximately 50% higher registrations are made in the wet state indicating softer structure.

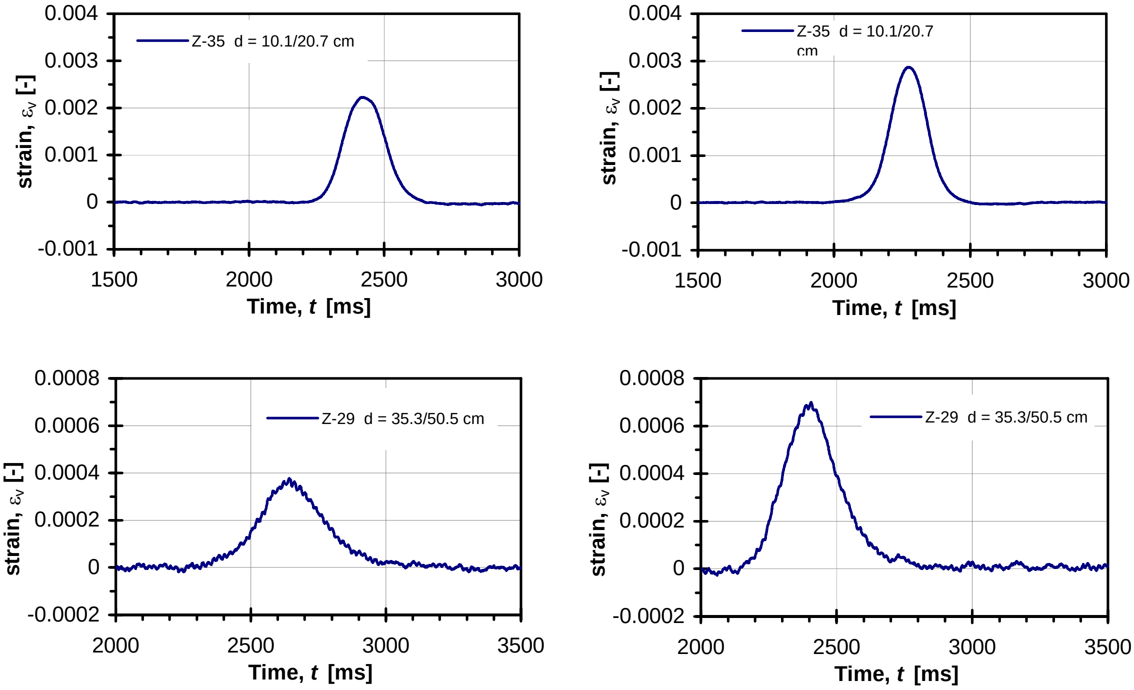

Figure 3: Induced vertical strain registration of two inductive coil sensors over the depth range 10.1 – 20.7 cm and 35.3 – 50.5 cm during a dual wheel loading conditions from both the moist (left) and the wet (right) phases of the test.

Figure 4 shows the induced horizontal strain measured from the strain gauges under the centre of one of the wheels at the bottom of the bituminous base due to a dual tyre loading combination after approximately 250,000 (moist state) and 750,000 (wet state) loading repetitions. Registrations in both the longitudinal (X) and the transverse direction (Y) are shown. Both directions show higher registrations in the wet state indicating less support from the underlying base course and subbase.

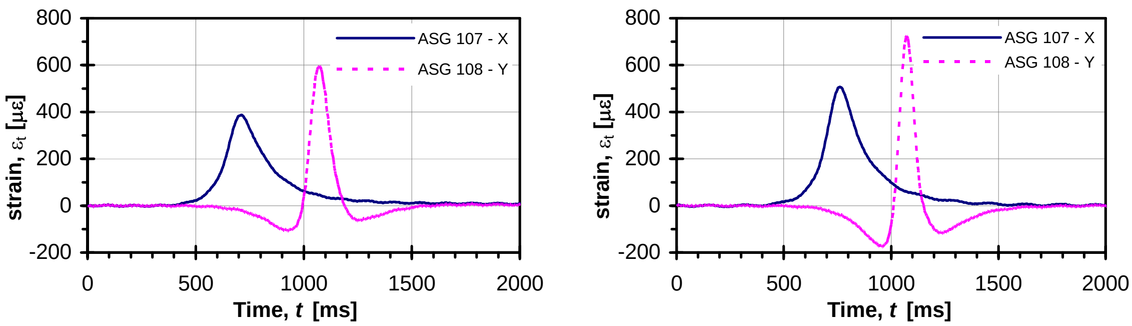

Figure 4: Induced horizontal strain registration of the ASG gauges at the bottom of the bituminous base during a dual wheel loading conditions from both the moist (left) and the wet (right) phases of the test. X = longitudinal direction and Y = transversal direction.

The development of sensors registrations during the main testing phase are further shown in Figures 5 and 6. Figure 5 shows the development of the vertical stress as registered at two different depths, 17.5 and 44.0 cm respectively. As shown in Figure 1 the uppermost located sensor is in the granular base course but the other one is in the sandy subgrade. During the first part of the main testing phase, that is load cycles 20,000 – 530,000 the registered vertical stress is quite constant for the sensor in the granular base. The sensor in the subgrade shows some increase in the registration as the number of load cycles increases. Thus, the subgrade’s stiffness is increasing with the number of load pulses indicating that some post-compaction is taking place as a result of the repeated load pulses. As the ground water table is raised, after 530,000 load repetitions, all pressure cells show significant reduction in their registrations. However as the test continues the structure seems to slowly regain its strength as both sensors increase their readings as the number of load repetitions increases.

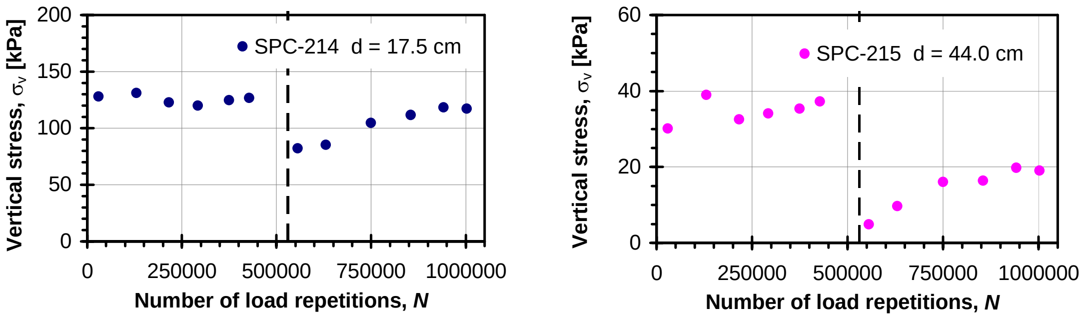

Figure 5: Induced vertical stress as measured by the soil pressure cells at two depths as a function of load repetitions. The depths are 17.5 (base course) and 44.0 cm (subgrade) respectively. The vertical dotted line indicates when the level of the ground water table was increased.

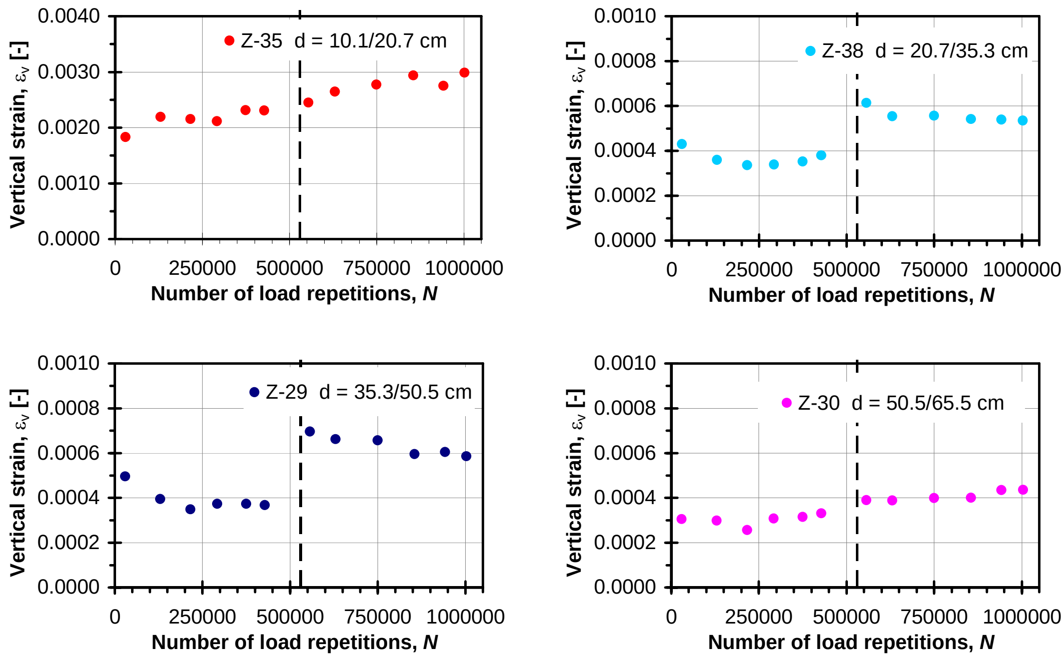

Figure 6: Induced vertical strain over four different depth ranges, 10.1 – 20.7 cm, 20.7 – 35.3 cm, 35.3 – 50.5 cm and 50.5 – 65.5 cm, as a function of load repetitions. The vertical dotted line indicates when the level of the ground water table was increased.

Figure 6 shows the development of the vertical strain as registered over four different depth intervals, 10.1 – 20.7 cm, 20.7 – 35.3 cm, 35.3 – 50.5 cm and 50.5 – 65.5 cm, respectively, see Figure 1 for overview of their locations. Figure 6 shows that the strain readings are quite constant during the first 530,000 load repetitions. After the ground water table was raised all sensors show higher readings. The two intermediate sensors, at 20.7 – 35.3 cm (granular subbase) and 35.3 – 50.5 cm (the uppermost part of the subgrade) indicate some strength recovery as the number of load repetitions increases but the two others did not.

5 MODELLING OF A PAVEMENT PERFORMANCE

The response of the pavement structure has been estimated through numerical analysis. For further details of the analysis method, see Erlingsson (2007). A nonlinear elastic behaviour has been assumed for the granular layers using a stress dependent stiffness modulus for the base course (May and Witczak, 1981). In a normalized form the stiffness can be written as:

$$M_r = k_1 \cdot p_a \cdot \left(\frac{3p}{p_a} \right)^{k_2} \qquad (1)$$

where k_1 and k_2 are experimentally determined constants, p is the mean normal stress level of the loading and p_a is a reference pressure, p_a = 100 kPa. The material parameters used in the numerical analyses for the response of the structure are given in Table 1.

Table 1: Material parameters of the different layers used for the response analyses.

Layer		Stiffness M_r [MPa]	Poisson's ratio ν [-]	k_1 [-]	k_2 [-]	Unit weight γ [kN/m^3]
Asphalt Concrete		5,000	0.35			25.0
Bituminous Base		5,000	0.35			25.0
Base Course – Unbound	moist		0.35	283.9	0.4	23.0
	wet		0.35	189.3	0.4	23.0
Subbase – Unbound	moist	180	0.35			22.5
	wet	120	0.35			22.5
Subgrade	moist	140	0.35			17.5
	wet	100	0.35			17.5

The accumulation of the vertical strain in the pavement materials is based on a best fit approach from repeated load triaxial testing. For all the unbound layers a simple three parameter work hardening model has been used (Tseng and Lytton, 1989):

$$\hat{\varepsilon}_p(N) = \varepsilon_0 \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \qquad (2)$$

where N stands for the number of load repetitions and ε_0, ρ and β are regression parameters. For the bituminous bounded layers the evolution of the plastic strain was based on (ARA, 2004):

$$\hat{\varepsilon}_p(N) = a_1 \cdot N^{a_2} \cdot T^{a_3} \qquad (3)$$

where a_1, a_2 and a_3 are model parameters and T is the temperature in °C of the layer.

The evaluation of the plastic strains is carried out within a reference framework (i.e. in a laboratory test) giving the model parameters and thereafter scaled to represent the accumulation of plastic strain under the actual field conditions according to Tseng and Lytton (1989):

$$\frac{\hat{\varepsilon}_p^{field}(N)}{\Delta\varepsilon_r^{field}} = \frac{\hat{\varepsilon}_p^{lab}(N)}{\Delta\varepsilon_r^{lab}} \tag{4}$$

where *lab* and *field* denotes the reference framework and the actual field conditions, respectively and $\Delta\varepsilon_r$ is the induced vertical resilient strain (Erlingsson, 2007 and 2008).

The parameters used for the permanent deformation predictions are further given in Table 2 and 3. They are based on repeated load triaxial testing in laboratory and values from the literature.

Table 2: Material parameters of the bound layers used for the permanent deformation prediction.

Layer	$\frac{a_1}{\Delta\varepsilon_r^{lab}}$ [-]	a_2 [-]	a_3 [-]
Asphalt Concrete	0.004	0.7	0.4
Bituminous base	0.004	0.7	0.4

No distinction is made in the parameters for the bound layers as to whether the structure was moist or wet as it is believed that even if some potential changes in their moisture content took place in the bound layers it would not affect their material behaviour. This is not the case for the unbound layers where their permanent deformation characteristics are highly dependent on the moisture content, see Table 3.

Table 3: Material parameters of the unbound layers used for the permanent deformation prediction.

Layer		$\frac{\varepsilon_0}{\Delta\varepsilon_r^{lab}}$ [-]	ρ [-]	β [-]
Base Course	moist	3.5	50,000	0.4
	wet	1.8	50,000	0.4
Subbase	moist	18	60,000	0.5
	wet	5.0	60,000	0.5
Subgrade	moist	186	80,000	0.6
	wet	285	80,000	0.6

6 RESPONSE BEHAVIOUR ANALYSIS

Figure 7 shows the results of the calculated as well as the measured induced vertical stresses and strains of the pavement structure for both moist and wet states. Here the loading consisted of a dual wheel configuration with a wheel load of W = 60 kN and a tyre pressure p = 800 kPa. A profile under the centre of one of the tyres is shown. The figure shows quite good agreement between the measured and calculated stresses and strains at all three depths.

As the asphalt concrete and the bituminous stabilised base were all together around 10 cm thick and quite stiff the vertical induced stresses decreased rapidly with depth and were around 100 kPa at the top of the unbound base and decrease approximately linearly thereafter with depth, see Figure 7a). The deviation between the measurements and the calculations in the base course and subgrade were rather small. It is clear that both the measured and calculated stresses were slightly lower in the unbound layer for the wet state. The average value from the nine pressure cells gave 18% lower registrations for the wet state. This was probably a result of vertical upward transport of moisture from the groundwater table after it was introduced. The increased moisture content decreased the stiffness of the respective layer, hence lower stress was registered.

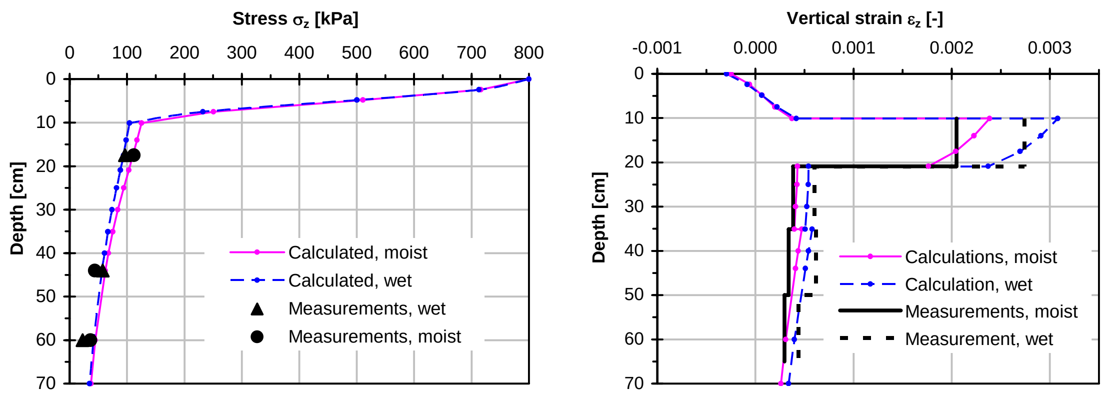

Figure 7: Vertical a) induced stress and b) resilient strain as a function of depth for both moist and wet structure. The loading consisted of a dual wheel configuration with a wheel load of W = 60 kN and a tyre pressure p = 800 kPa. A profile under the centre of one of the tyres is shown.

Figure 7b) shows the average measured vertical strains of all the strain sensors as well as the calculated strains. The numerical analysis with the nonlinear material parameters of the unbound base captured quite well the high measured strains there. For the subbase and the subgrade a linear elastic model seems to give reasonably good agreement with respect to the measurements. Higher strain values are registered for the wet state. The average increase of the ten strain sensors that gave trustworthy results resulted in about 57% higher registrations for the wet state. The vertical strains were therefore much more affected by the increased moisture than the vertical stresses.

7 RUTTING PREDICTION

Figure 8 shows the results of the rutting prediction as well as the measurement of accumulated permanent deformation, as a function of load repetitions. The loading consisted of a dual wheel configuration with a wheel load of W = 60 kN and a tyre pressure of p = 800 kPa. The figure shows the development of the permanent deformation for one million load repetitions in the uppermost 30 cm of the subgrade (Sg), the subbase (Sb) and base course (BC). Also the total rut as measured on the surface is shown. After 530,000 load repetitions water was pumped into the test pit until the groundwater table reached the level of 30 cm below the top of the subgrade. All layers show accelerated development of permanent deformation after raising the groundwater table. The subgrade showed the largest increase. After 500,000 load repetitions the evolution of permanent deformation seems to have reached stagnation but after the water was introduced in the subgrade further permanent deformation started to develop. The subbase and the base course also show some increase in permanent deformation behaviour after water was introduced but not to the same extent as the subgrade.

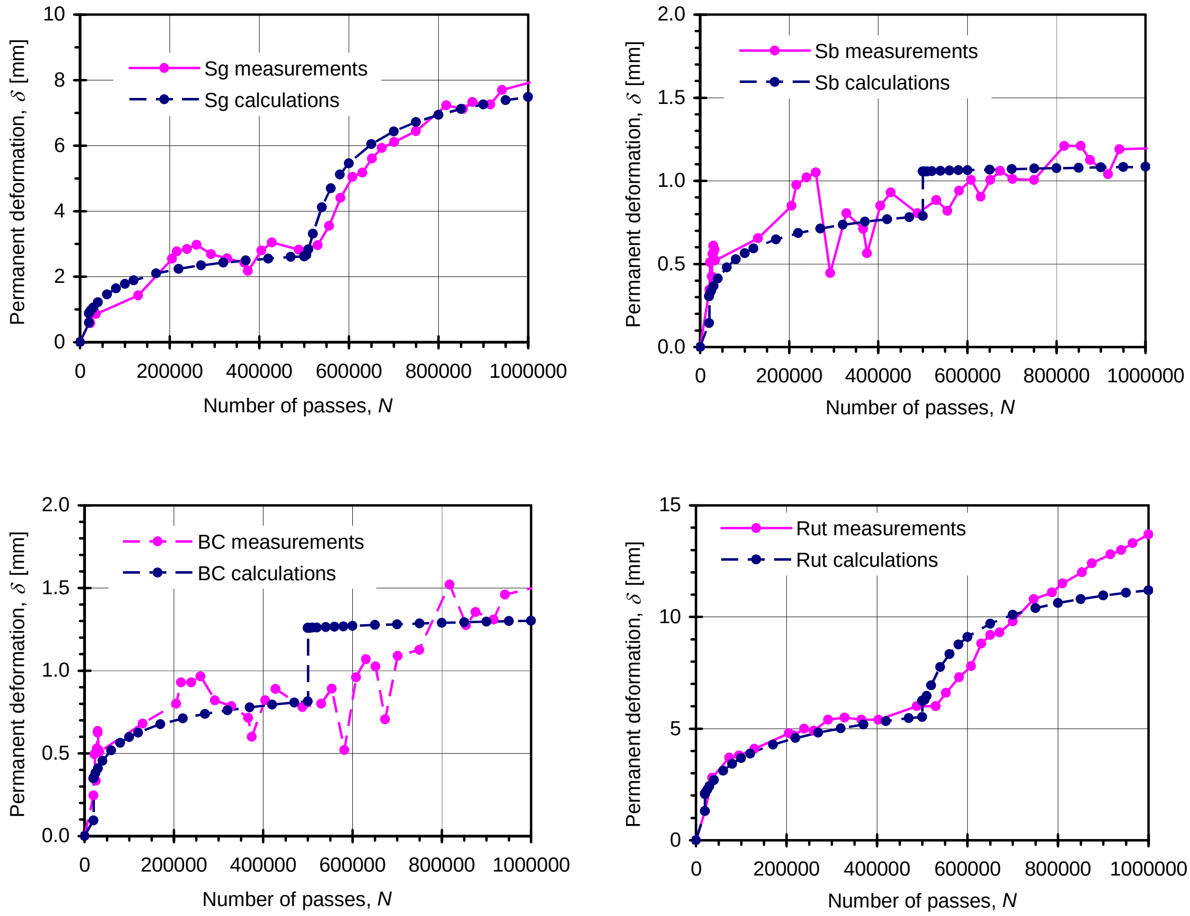

Figure 8: Permanent deformation evolution as a function of the number of load repetitions. Sg = subgrade, Sb = subbase and BC = Base Course. One million load cycles are shown. After 530,000 repetitions water was gently pumped into the structure, raising the ground water table and the test continued.

All the resilient and permanent strain measurements were carried out above the new groundwater table that was introduced. Thus the sensors were not directly saturated. However, increase in resilient and permanent strain was registered in all the unbound layers. This was probably due to the capillarity (suction) of the layer of the transport moisture suctioned vertically upward above the groundwater table. Hence, the water content of the unsaturated layers increased. Unfortunately no measurements of the water content were made in the structure so this has not been verified. The largest influence of the groundwater table was in the sandy subgrade. Both the subbase and the base course were much coarser and therefore had a much lower ability to attract water. They were therefore not affected to the same extent as the subgrade.

8 CONCLUSION

The paper presents results from an HVS testing of one pavement structure carried out in a concrete test pit under constant environmental conditions. Results regarding the response of the

structure due to wheel loading are given as well as permanent deformation development as a function of the number of load repetitions. More than 1,000,000 load repetitions were applied. After 530,000 load repetitions water was introduced in the test pit and additional 500,000 load pulses were applied. This increased the development of the rutting in the unbound layers.
The major findings from this study were:

- HVS testing helps to increase our understanding of pavement behaviour under external heavy wheel loading. HVS tests can be used to help develop a mechanistic based pavement design method.
- Numerical analysis where nonlinear base behaviour is modelled can predict the response behaviour of the structure with reasonable accuracy.
- Rutting prediction using a simple power law function can give good agreement with actual measurements of permanent deformation development.
- Raising the groundwater table increased both the resilient and the permanent strain of all unbound layers above the groundwater table in the pavement structure. This is probably due to increased moisture content in the unbound layers.
- After ground water was introduced, the strength is partly regained as the test continues. This might be due to some additional compaction which was lost as the water was introduced.

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