Permanent Deformations Predictions of Unbound Base Materials Based on Results from a Testing Box Technique

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ABSTRACT

A test box method has been developed and used to analyse response and permanent deformation characteristics of unbound granular materials. The box is 800 × 800 × 800 mm and has been used to test two layered structures, an unbound base course layer over subbase, totally 500 mm in high. The loaded area is in the centre of the box and consists of a circular 100 mm diameter plate. The response of the tested structure is measured with ten deformation sensors located at two high levels. The instrumentation gives the possibility to study the load spreading in the material due to applied vertical loading. Different applied load levels have been used. Both the response measured as well as the development of the permanent deformation have been modelled using the k-theta model for the measured resilient response and three simple load hardening models have been used for permanent deformation. A set of model parameters have been estimated that gave good agreement with the measurements. These parameters are then used for verification of the test results with data from Heavy Vehicle Simulator (HVS) - measurements.

1 INTRODUCTION

Unbound Granular Materials (UGM) has a major role in bearing capacity of pavements specially when dealing with thin structures. Realistic modelling of the unbound layers response and degradation is therefore important to road owners in order to be able to make a realistic life cycle assessment prediction of the pavement structure.

Pavement design methods in the past have relied on empirical approach that has not been able to predict performance very accurately. New Mechanistic-Empirical (M-E) pavement design methods are therefore being developed in different countries with the main purpose of adequately predicting pavement performance as a function of time. One of the important parts in M-E calculations is linked to realistically modelling al all layers response and deterioration. The study presented here has therefore focused on investigating the applicability of methods to model the UGM structural behaviour. For that purpose a text box technique has been used where two layers, an unbound base course resting over a subbase layers have been tested and thereafter analysed and compared with numerical simulations.

2 CHARACTERISTICS OF UNBOUND GRANULAR MATERIALS

Unbound granular materials (UGM´s) perform an important structural role in flexible pavements. During road construction these materials carry the heavy construction traffic and provide a foundation on which higher layers are placed and compacted. In completed pavements the materials act as a load spreading layer and, when successfully constructed, shows high resilient moduli to reduce the deformation of upper bituminous layers, and resist internal structural deformation which might contribute to surface rutting. UGM´s have further an important role in draining away quickly and securely excessive water that might enter the pavement structure.

The responses of UGM´s are of a different character and magnitude, depending on the applied load, and include both reversible (elastic or resilient) and irreversible (permanent) deformation. As the load magnitude increase both the resilient and permanent contribution increases, see Figure 1.

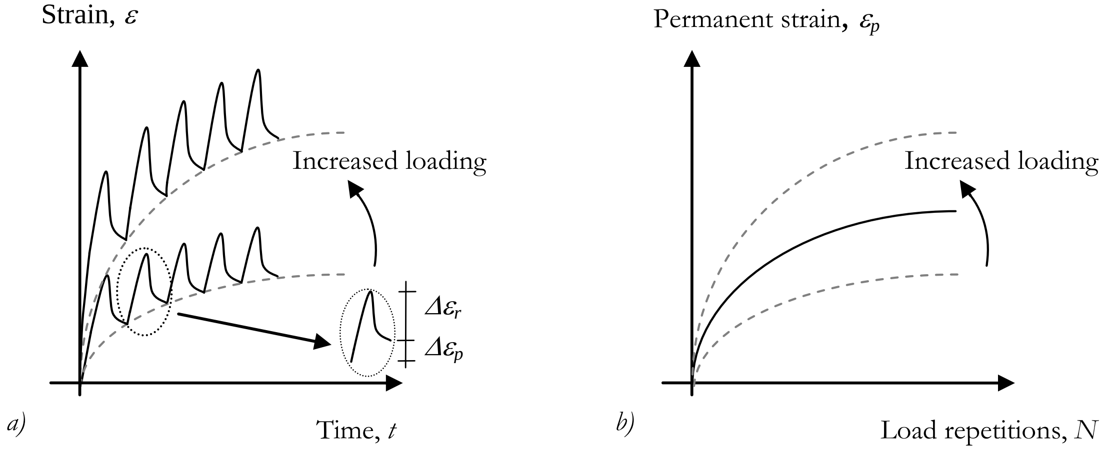


Figure 1: Effects of number of load applications and increased loading on development of the permanent strain (Erlingsson, 2010).

Figure 1a) shows the development of strain in unbound granular material subjected to dynamic load pulses. During each load pulse the total induced strain $\Delta\varepsilon_{tot}$ in the material can be divided into elastic and a plastic part, thus $\Delta\varepsilon_{tot} = \Delta\varepsilon_r + \Delta\varepsilon_p$. As the plastic strain remains after each loading, it is accumulated as the number of load increases as indicated by dotted line. Increasing the magnitude of the load pulses increases the rate of accumulated permanent strain although the shape of the accumulated strain curve remains the same as shown in Figure 1b).

The resilient response of UGM is stress dependent (May & Witczak, 1981; Uzan, 1985; Lekarp et al., 2000). This nonlinear behaviour can be taken into account by using a stress strain relationship where the stiffness is given as:

$$M_r = k_1 \cdot \theta^{k_2} \qquad (1)$$

where θ is the sum of all the three principal stresses and k_1 and k_2 are material properties.

Number of models has been suggested for describing the accumulation of permanent deformation of unbound materials.

Tseng and Lytton (1989) suggested a simple three parameter model for prediction of the permanent deformation:

$$\varepsilon_p(N) = \varepsilon_0 \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \tag{2}$$

where ε_0, ρ and β are experimentally determined material properties. Tseng and Lytton further assumed that the relationship between the elastic and permanent strain in the field is the same as in the laboratory. This assumption is expressed as follow.

$$\frac{\varepsilon_p^{lab}}{\Delta\varepsilon_r^{lab}} = \frac{\varepsilon_p^{field}}{\Delta\varepsilon_r^{field}} \tag{3}$$

If the two expressions (2) and (3) are combined then the permanent strain in the field (or at other load levels) can be estimated based on laboratory experiments as

$$\varepsilon_p^{field}(N) = \frac{\varepsilon_0}{\Delta\varepsilon_r^{lab}} \cdot e^{-\left(\frac{\rho}{N}\right)^{\beta}} \cdot \Delta\varepsilon_r^{field} \tag{4}$$

Two empirical models have been proposed where the state of stress with regard to the internal static failure line are used to scale the contribution of permanent deformation (Gidel et al., 2001; Korkiala-Tanttu, 2008). Gidel et al. (200l) suggested a model that predicts the vertical permanent strain as a function of the state of the stress and number of the load repetitions:

$$\varepsilon_p(N) = \varepsilon_{1p}^0 \cdot \left(1 - \frac{N^{-B}}{N_0}\right) \cdot \left(\frac{L_{max}}{p}\right)^n \cdot \frac{1}{\left(m + \frac{s}{p} - \frac{q_{max}}{p}\right)} \tag{5}$$

Where ε_{1p}^0, *n*, and *B* are material constants, N_0 is a reference number of load repetitions, $N_0 = 1$ and p_a is a reference stress, $p_a = 100$ kPa. Further is:

$$L_{max} = \left(p_{max}^2 + q_{max}^2\right)^{1/2}, \; p = \frac{1}{3} \cdot (\sigma_1 + 2\sigma_3) \; \text{ and } \; q = (\sigma_1 - 2\sigma_3)$$

and *m* and *s* are parameters describing the Mohr Coulomb static failure line.

Korkiala-Tanttu (2008) developed a model for calculation of the permanent deformation in unbound materials given as:

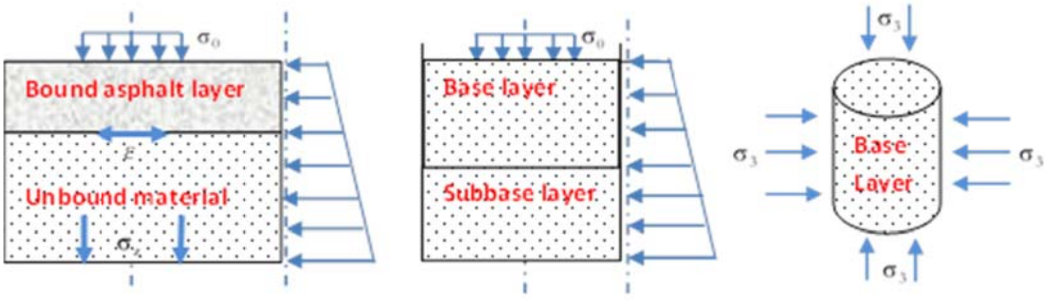
$$\varepsilon_p(N) = C \cdot N^b \cdot \left(\frac{R}{A - R}\right) \tag{6}$$

where *C*, *b* and *A* are material parameters ($A = 1.05$) and *q* is the deviatoric stress. Further is:

$$R = \frac{q}{q_f} \quad \text{and} \quad q_f = s + m \cdot p$$

3 TESTING BOX

The non-linear response at any location below the surface can only be measured in terms of deformation or strain. At the same time the characteristics of a real road in terms of confining stresses, which increase with depth, should be considered as an important factor affecting the resistance of the material to the development of permanent deformation. A testing box simulates the confining more realistically compared to Repeated Load Triaxial (RLT) testing, see Figure 2.



a) Real pavement **b)** Testing box **c)** Triaxial

Figure 2: Variation of confining pressure in a a) real pavement and laboratory simulation with b) testing box and c) triaxial testing specimen (Not to scale).

In the study presented here a box 800 × 800 × 800 mm is used to test two layered structures, an unbound base course layer over subbase, totally 500 mm in high. The layout of the testing box is illustrated in Figure 3. The loaded area is in the centre of the box and consisted of a circular plate with a 100 mm diameter. The response of the tested structure is measured with ten deformation gauges located at two high levels. The instrumentation gives the possibility to study the load spreading in the material due to applied vertical loading.

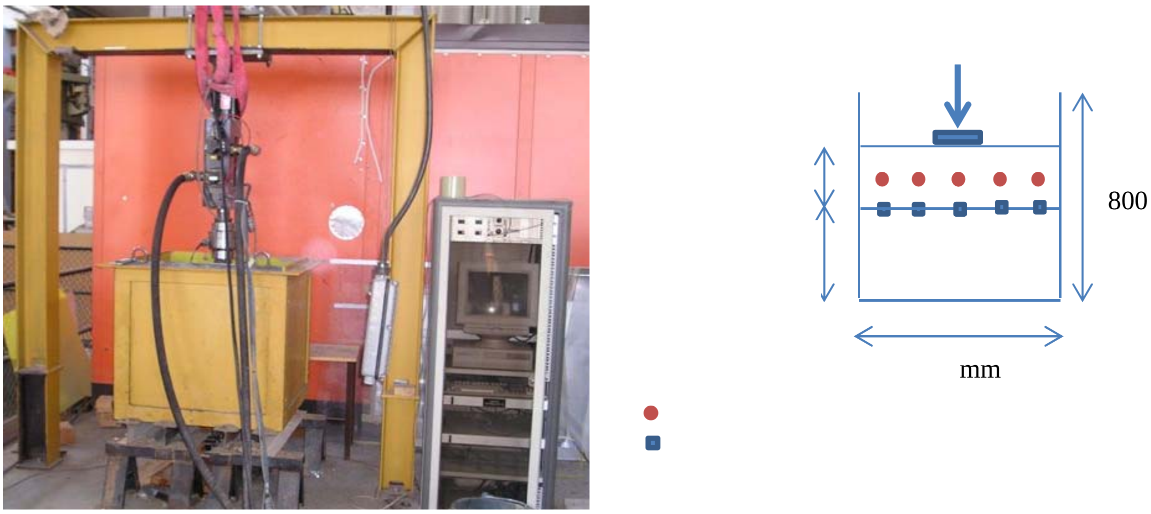


Figure 4: a) The testing box along with the loading and control unit. b) Five deformation gauges within the base course material and five at the top of the subbase.

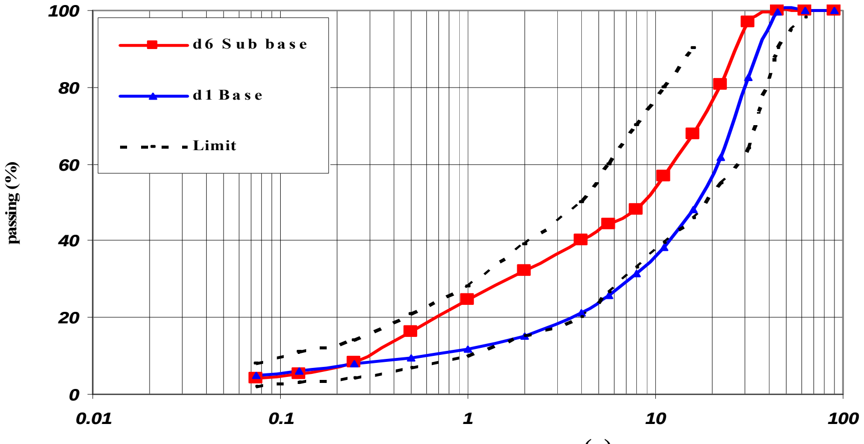
4 THE MATERIALS AND TESTING PROCEDURE

The base course material (d_1) used in the experiments is a 0-40 mm crushed material frequently used in Swedish pavements. The subbase material (d_6) is a natural gravel material 0-100 mm in size. The properties of these materials are shown in Table 1. These two materials are most common frequently ones used as base material in pavements in southern Sweden.

Table 1 Properties of the two materials used in experiments

Material Properties	Base course material d_1	Subbase material d_6
Dry density (g/cm^3)	2.08	2.25
Optimum moisture content (% weight)	7.7	6.0
Particle density>5,6 mm (g/cm^3)	2.73	2.57
Flakiness ratio	1.51	1.37
Aggregate impact value	52	55
Nordic Ball Mill Value	23.5	25.1

Figure 5 illustrates the particle size distribution curves for the two materials used in the experiments in the testing box. The blue curve represents the base course 0-40 mm crushed material and the red curve shows the subbase material. The dash-point curves are the limit values suggested.



(a)

Figure 5: The particle size distribution curves

The mixed material is compacted by a small vibration hammer (hand stamping 15 kg). The amount of material compacted each time is almost 40 mm in thickness. The compaction is carefully conducted around the steel bars connected to the displacement gauges to avoid any damage to the measuring devices. A target compaction of 98% was achieved according to measurements conducted. The in-situ dry density is calculated and since the volume of the testing box (800 × 800 × layer thickness) is constant, then the amount of necessary aggregate required to reach the desired degree of compaction can be calculated for each layer.

The layer construction, the so called specimen with all transducers is covered with plastic for 48 hours. This gives the specimen the possibility to distribute the water content evenly. This procedure was applied in all measurements.

5 TEST RESULTS

The test results explained here are divided into two groups. The first part is the results of the response analysis discussed in 5.1 and the second part discussed in 5.2 is about the permanent deformation.

5.1 Response analysis

The response measurements have been conducted with four different vertical load levels and two different layer thicknesses. Each test program consists of four measurements with four vertical loads ranging from 3.75 to 15 kN. The loading of the specimen starts at 0.25 kN and the load is increased by increments of 0.25 kN/s until the desired maximum load (3.75, 7.5, 11.25 or 15 kN) is reached. The diameter of the loading plate is 100 mm in all experiments. The displacement of each gauge is registered under the certain applied load before the next load level is applied. A short period of approximately 10 minutes between load levels, when going from one load level to the next is used to reprogram the loading unit and to create a new file to register the new displacement. This procedure continues until all four vertical loads are applied to the specimen. Typical results are shown in Figure 7.

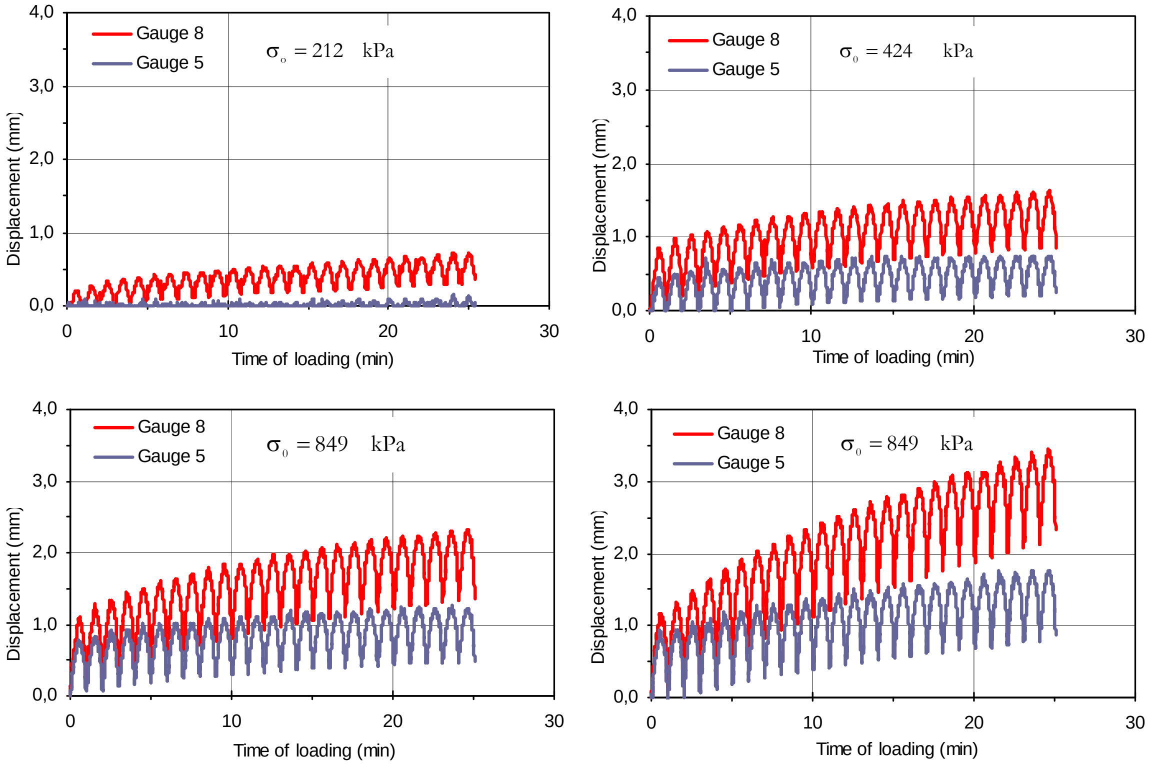


Figure 7: Displacements of gauge 5 (40 mm depth) and gauge 8 (80 mm depth) at 80mm base layer thickness and different vertical stresses amplitude σ_0 with a frequency of 1Hz.

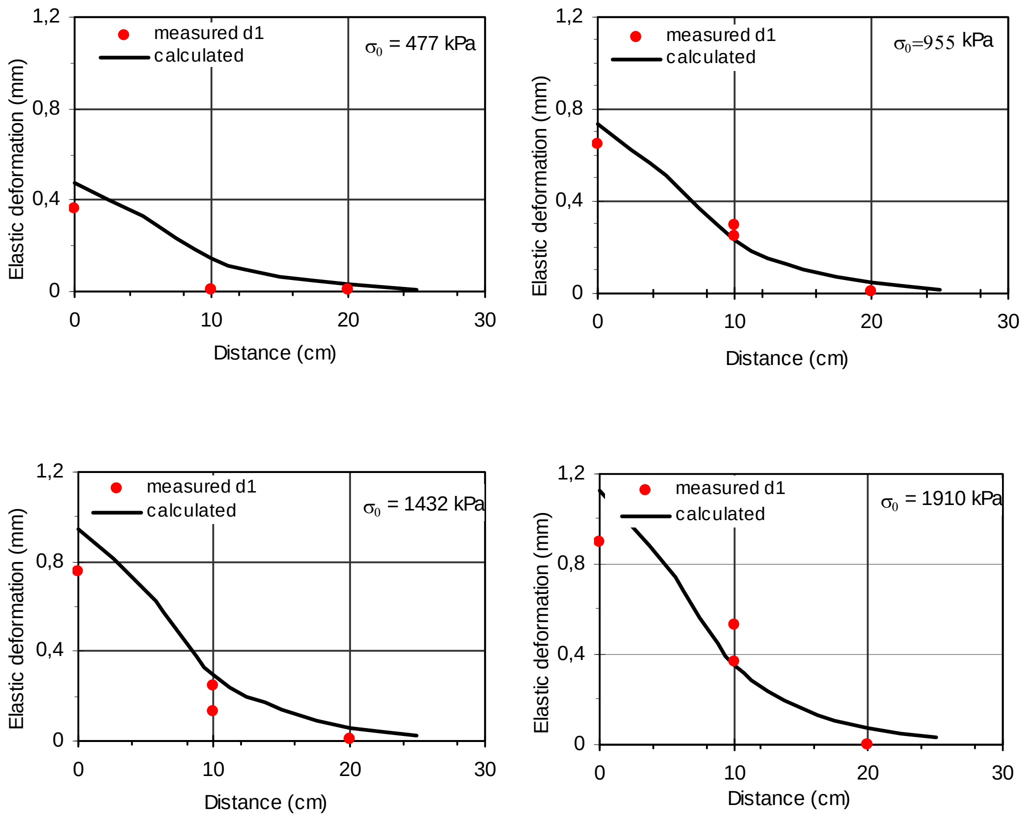


Figure 8: Comparison between numerical model (Non- linear) and the measurements from the testing box for material d_1 in the middle of base course with four different vertical stresses and loading plate of 100 mm.

In order to compare the results from the experiments in the testing box with an established testing method, the d_1 base material was chosen and measurements with same condition as the testing box were conducted in Repeated Load Triaxial (RLT) equipment in which gave the k_1 and k_2 values for the k-θ model as k_1 =21.71MPa and the k_2 =0.39. These values have thereafter been used to numerically simulate the response in the box using the KENPAVE (Huang, 2004) software. The results are shown in Figure 8 for four different load levels.

Figure 8 shows the results of the comparison between the numerical method and the testing box for material d_1 at the boundary between the base and subbase material and at a depth of 80 mm. Four different loading cases are shown ranging from relatively low loading to very high loading. The calculated and measured values in the testing box show a relatively good correlation at the point beneath the loading plate. When the vertical stress is low, the measured value is lower than the calculated value. As the vertical stress increases the measured values become closer to the calculated values.

5.2 Accumulation of permanent deformation

To evaluate the permanent deformation characteristics, series with 100,000 load repetitions were conducted for different load levels. The accumulation of permanent deformation was thereafter modelled using the three mentioned models. The thickness of the tested base course layer was 150 mm. The results are shown in Figure 9.

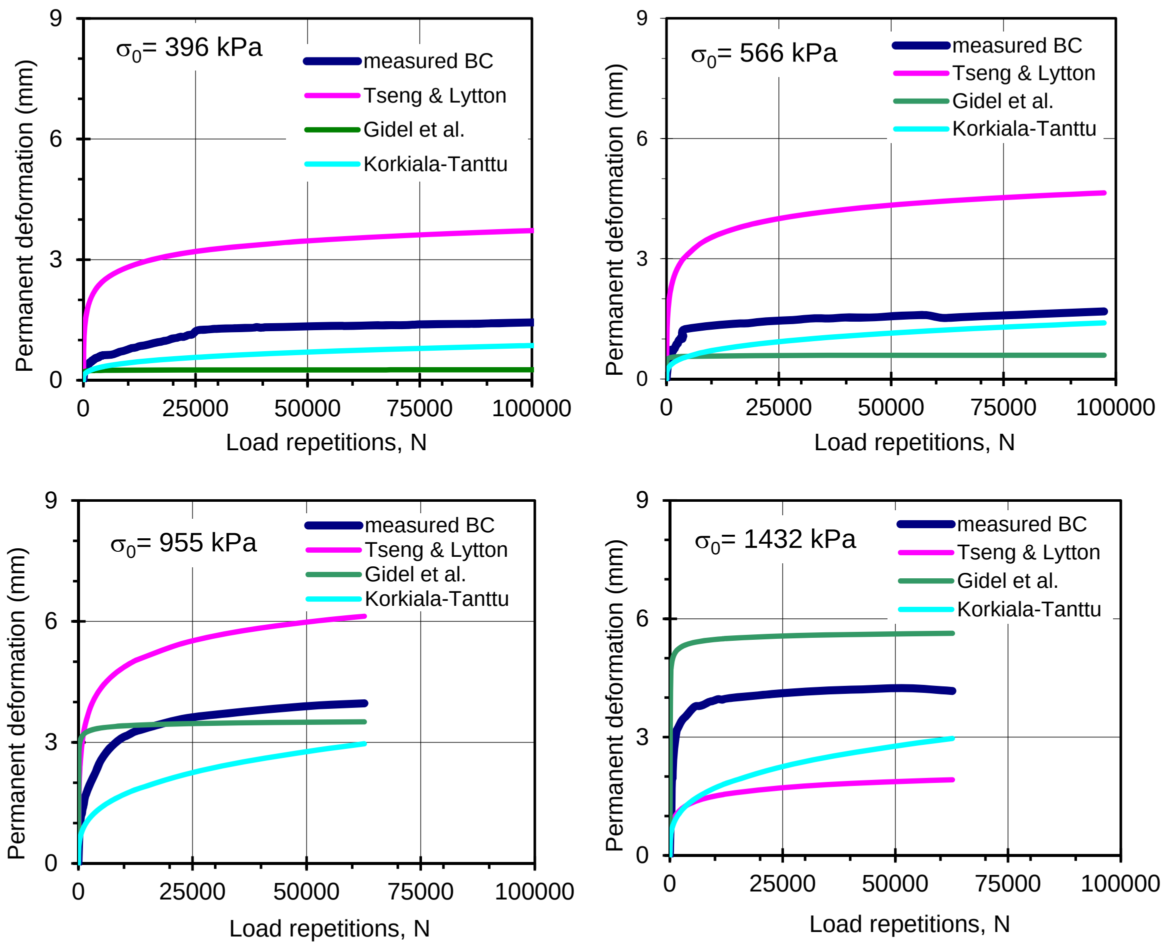


Figure 9: Measured and calculated accumulated permanent deformation as a function of the number of load repetitions of different surface loading in the middle of the base course.

The results shown in Figure 9 are the measured and calculated values of the permanent deformation in the middle of the base course. The model proposed by Korkiala-Tanttu (2008) shows a very good correlation with the measured values from the testing box. The model suggested by Tseng & Lytton (1989) on the other hand predicts values that are higher than the measured values in three cases. When the applied stress is 1432 kPa the model predicts lower values than the calculated one by the testing box. The model suggested by Gidel et al. (2001) predicts lower deformation at low stresses and higher values at high stress levels (Parhamifar, 2011). Material parameters that are used are shown in table 2.

Table 2 Three used models in analysis and material parameters for permanent deformation models.

Material	c	ϕ	C	b	ε_{1p}^{0}	B	n	m	$\frac{\varepsilon_0}{\varepsilon_{1r}^{lab}}$	ρ	β
	[kPa]	[°]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
d_1	70	70	5.0·10	0.3	1.5·10	0.3	0.6	2.73	20	2200	0.2
d_6	45	50	1.2·10	0.3	2.5·10	0.3	0.6	2.05	5.45	3000	0.2

5.3 Comparison with data from Heavy Vehicle Simulator (HVS)

One major concern in modeling and prediction of pavement material responses based on laboratory assessments of the materials is to verify the suggested model with data from existing pavements. Pavement materials do not experience the same loading and climate conditions as in a controlled laboratory environment, and therefore elastic and plastic material responses can differ. In laboratory measurements the magnitude of the applied vertical load is constant and well defined during tests, while in pavements the loading conditions caused by traffic are constantly changing in magnitude of the axle loads, tire pressures and duration of the loading. Climate factors, such as temperature and moisture content, which affect the behaviour of the materials in pavements, are controlled and monitored in laboratory environments.

To study the response and performance characteristics (deformation behaviour) of materials in flexible pavements, several series of Accelerated Pavement Testing (APT) have been conducted using the Heavy Vehicle Simulator (HVS) at the Swedish Road and Transport Research Institute, VTI (Wiman, 2001; Wiman, 2006; Wiman & Erlingsson, 2008).

Accelerated pavement testing is one way to study deterioration of pavement materials subjected to internal loading caused by traffic. The heavy vehicle simulator is frequently used to investigate the gradual development of material response and performance. This method could be considered as field measurement and applied to existing pavements, but could also be classified as a full scale laboratory measurement method. Any desired pavement with different material layers can be constructed, instrumented and loaded in a laboratory environment. The results of measurements with HVS are used in pavement design to acquire a better understanding of material performance.

The data collected from one of these measurements is used here to verify the results from the testing box as given in Table 2.

The first pavement structure that was tested using the HVS facility in Sweden was called HVS-SE01, where a thin pavement was built and instrumented as shown in Figure 10 (Wiman, 2001). The main objective of this test and measurements was to learn more about the response and performance of the pavement materials subject to external dynamic loading.

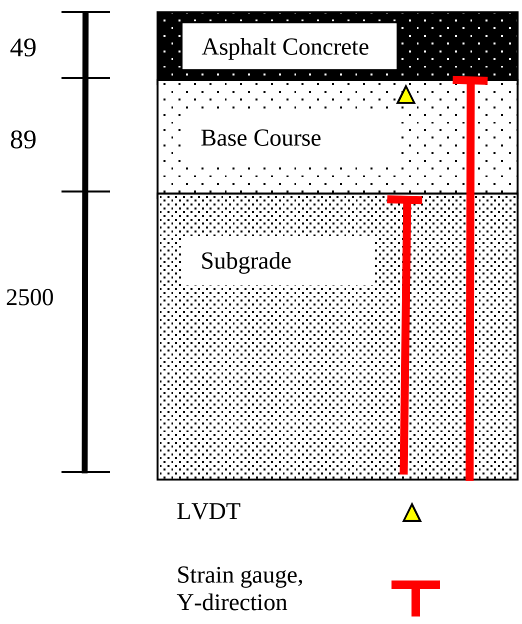


Figure 10: The test structure used in HVS-SE01 with instruments placed at different levels

The structure shown in Figure 10 is composed of three layers. The first layer is a dense graded asphalt concrete type ABT16 with actual thickness of
49 mm. The second layer is a granular base course with a maximum density of 2386 kg/m^3 and actual thickness of 89 mm (crushed material with similarities to the material used in the testing box). These two layers are supported by a sandy subgrade with a thickness of about 2500 mm and a density of 1665 kg/m^3.

Table 3 Properties of the granular base layer in SE-01

Max. dry density	2386 kg/m^3
Optimum water content	-
Isotopic measure: Dry density	2242 kg/m^3
Isotopic measure: Water content	5.6 %
Degree of compaction	94.0 %
Static plate loading test, E_{V1} Method: DIN18134	73 MPa
Static plate loading test, E_{V2} Method: DIN18134	148 MPa
Static plate loading test, E_{V1}/E_{v2} Method: DIN18134	2.1

The test structure HVS-SE01 was pre-loaded with 20,000 load repetitions of a 30 kN single load with a tyre pressure of 700 kPa and at 10°C pavement temperature. After response measurements due to pre-loading, the actual measurements started. The applied load was increased to 60 kN and measurements continued up to 1,000,000 load **r**epetitions. The load was once again increased to 80 kN with a tyre pressure of 1000 kPa and measurements continued up to 2,000, 000 load applications. The load applications continued with 35,000 repetitions but no data was registered.

The measurements were again continued by applying 60 kN and at normal surface stress of 800 kPa up to 2,300,000 load applications. The final maximum rut depth was registered as 46.60 mm (Wiman, 2001).

A numerical analysis using the multi-layer system KENPAVE was conducted to calculate the theoretical values of the stresses and strains induced in the base course layer. The results of the calculation were then used as data for three models based on Korkiala-Tanttu, Gidel et al., and Tseng & Lytton to determine the permanent deformation. The results obtained from the three models were compared to the measured values of the permanent deformation from measurements with HVS-SE01.

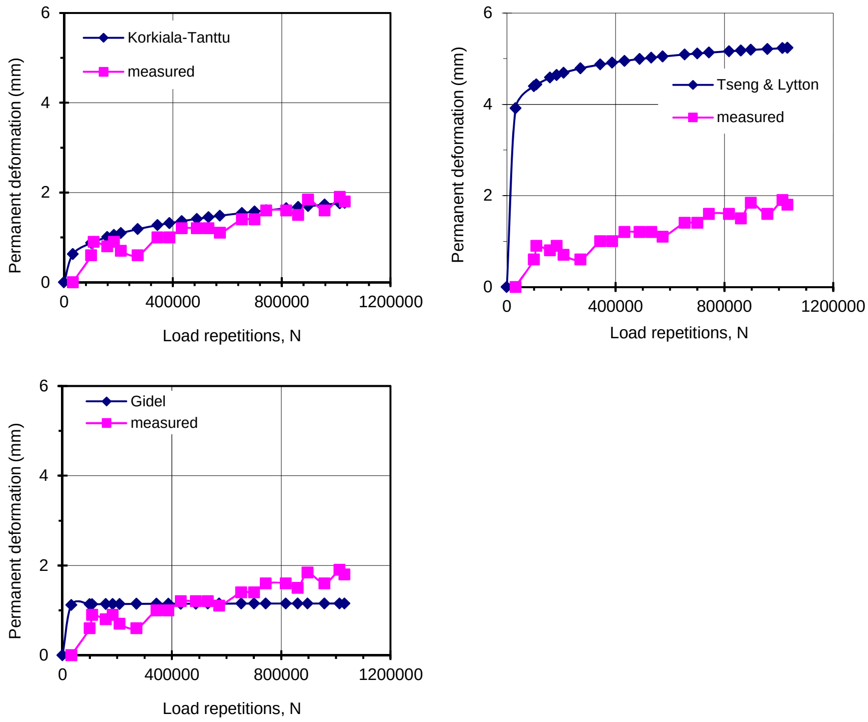


Figure 11: The results of comparisons between measured and calculated values of the permanent deformation in base course for three different models

As illustrated by Figure 11 there is good correspondence between the measured values in HVS-SE01 and calculated values of the Korkiala-Tanttu model. The initial deformation and development of the permanent deformation predicted by the model are very similar to measured values by HVS-SE01. Both predicted and measured developments of the permanent deformation are identical and both measured and calculated values show the same final maximum deformation at the end of the measurements. The similarities in the results indicate that the chosen material parameters for the Korkiala-Tanttu model are adequately adjusted to predict permanent deformation.

The predicted values by Gidel et al. (2001) are slightly different compared to the measured values. The development of initial deformation predicted by the model is very similar to the measured values. The model predicts very little development in permanent deformation and shows a steady state where very little deformation takes place.

The predicted values by Tseng & Lytton are almost 2.5 times higher than the measured values, which indicate that the material parameters need a calibration factor to adequately adjust the prediction of permanent deformation.

6 CONCLUSIONS

A testing box method has been developed and used to analyse response and permanent deformation characteristics of unbound granular materials. The box is 800 × 800 × 800 mm and has been used to test two layered structures, a typical crushed granular unbound base course layer over gravelly subbase, totally 500 mm in high. Both response and accumulation of permanent deformation has been studied. The measured response behaviour is compared with numerical analysis using the k-theta model to capture the stress dependency of the unbound material. Generally good agreement is achieved. The permanent deformation behaviour is modelled using three simple performance models. Two of the models used here to predict the performances of unbound granular materials are based on the static failure line.

The results of the experiments when compared to values predicted by the three mentioned models are promising. At low stress values the Tseng & Lytton model predicts higher deformations while the models proposed by Gidel et al. and Korkiala-Tanttu predict permanent deformations closer to the measured values. When the applied vertical stress is higher than 1000 kPa the model suggested by Gidel et al. predicts higher deformations than the measured values and Korkiala Tanttu and Tseng & Lytton predict values lower than the measured values. The model proposed by Korkiala-Tanttu in general gives the closest correspondence with the measured values from the testing box.

The results of comparison of data from HVS-measurements with the testing box showed good agreement between the Gidel and Korkila-Tanttu models.

Although adequate results are obtained, these models need to be improved, as does the procedure for estimating their parameters.

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