CYCLIC TRIAXIAL TESTS ON REINFORCED BASE COURSE MATERIAL

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ABSTRACT: This paper presents the results from large-scale triaxial tests on base course material reinforced with various types of geosyntetic reinforcement. The test samples are 600 mm high and 300 mm wide. The triaxial test program is part of the research project GeoRePave aiming at the development of a design method for paved roadways with reinforced base course layer. The design method is intended for implementation in mechanistic-empirical pavement design codes and will include a response model and a damage model. The damage model will describing the accumulation of vertical permanent strain in the pavement layers as a function of traffic load count. The model parameters for the damage model must be determined from cyclic load tests on the base course materials. The large-scale cyclic triaxial tests have been performed to assess the influence of reinforcement on the development of permanent vertical strain. These tests are also used to assess the influence of different types of geosyntethic reinforcement on the properties of base aggregate material models contained in the response model. The results from the cyclic triaxial tests show a significant reduction in permanent deformation for the reinforced samples.

1 INTRODUCTION

The development of permanent deformations is an important design criterion in road design. Several different models for prediction of permanent deformation in base course material have been proposed. The material parameters for these models are usually determined in cyclic triaxial tests.

Both field experience and model tests show beneficial effect of reinforcement in unbound base course aggregates. Reinforced base courses do typically show reduced permanent deformation compared to unreinforced. In an attempt to determine the influence of reinforcement on permanent deformation, large scale cyclic triaxial tests have been performed on both reinforced and unreinforced samples. The testing equipment, procedures and results from cyclic triaxial tests using four different types of reinforcement and one crushed rock aggregate is presented in this paper.

2 TRIAXIAL TEST EQUIPMENT

2.1 *Sample preparation*

Sample preparation is an important stage in triaxial testing of unbound base course aggregate. The density of the material influences the behaviour significantly. Especially is the resistance against permanent deformation highly dependent on the density.

The samples tested in this project were compacted using a vibrating plate compactor shown in Figure 1. The material was placed in five layers in a mould and each layer was compacted with the vibrating plate. Each layer was compacted to the target density.

To transfer the sample from the compaction mould to the latex membrane with a minimum of disturbance, special equipment has been constructed. This equipment secure that the sample is confined with internal vacuum all the time. In this way the properties that are built into the material during compaction can be kept relatively intact.

2.2 *Large triaxial testing apparatus*

A sketch of the triaxial testing apparatus is shown in Figure 2. The samples size is 600 mm in height and 300 mm in diameter. The apparatus is designed with the possibility to apply cyclic load both for the vertical and the confining stress. In the tests in this project the confining stress is kept constant within each loading sequence.

2.3 *Instrumentation*

The normal on-sample instrumentation used at NTNU/SINTEF including two LVDTs for measuring axial deformation between end plates and six LVDTs mounted on callipers for measurement of radial deformations, is shown in Figure 2.

To study the influence zone of the reinforcement, eight additional sensors for local measurements of axial deformation were included. The axial LVDT was attached to the sample by glue on the rubber membrane at the centre of the sample. The LVDT-cores were attached to a piece of metal glued to the membrane at different distances from the centre. The measuring distances were 75, 100, 200 and 300 mm from the middle of the sample and upwards.

2.4 *Base course aggregate*

The target density for the aggregate was 2202 kg/m^3 with a moisture of content 3.6 %. These values were measurement in a full-scale field tests performed by the US army cops of engineers Cold Regions Research and Engineering Laboratory” (CRREL).

Figure 1 Compaction equipment

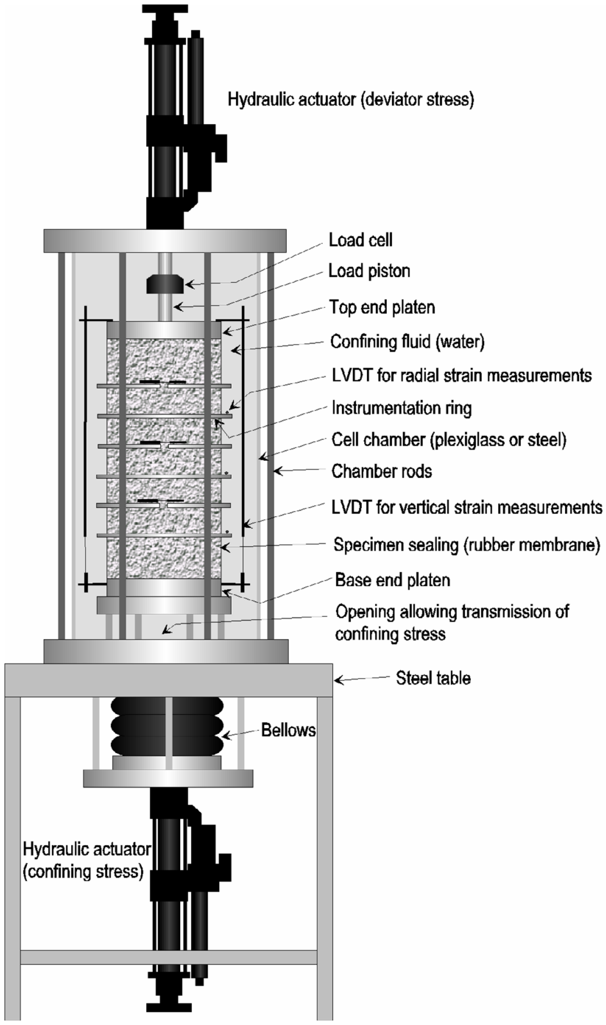

Figure 2 Cyclic triaxial test equippment

2.5 *Reinforcement*

Four different types of reinforcement were used in the tests. The reinforcement types had different mechanical and physical properties, but the failure strength and strain were in the same range. Strength and strain properties are given in Table 1.

Table 1 Reinforcement types

Type	Aperture size mm	Strength at failure kN/m MD, CMD	Strength at 2% strain MD, CMD
Polypropylene Grid	24 x 36	17.0, 29.0	6.0, 9.0
Polypropylene woven, slit film	NA	30.7, 30.7	1.6, 8.7
Woven polyester grid coated with PVC	25 x 25	45.5, 32.0	11.9, 5.0
Composite of PP non-woven and grid of polyester yarns	40 x 40	36.0, 36.0	4.4, 4.4

3 TRIAXIAL TESTING PROCEDURES

Due to the large sample size the sample preparation and instrumentation procedure was rather time consuming. Two to three days where required for one sample. It was therefore decided to run both resilient modulus and permanent deformation loading procedures on each sample.

3.1 *Resilient modulus procedure*

To investigate the stress dependent non-linear behaviour and the resilient properties of a granular material, tests at many different stress levels are performed. However, only 100 pulses are needed at each stress level. In this project we have used the procedure presented in Table 2 that is likely to be included in the new 2002 PDG in the USA.

3.2 *Permanent deformation procedure*

In order to make the different samples as comparable as possible the resilient tests where stopped at a total strain of 1% for all samples.

To determine the resistance against permanent deformations and to investigate the long term behaviour of the material, it is necessary to apply more pulses than for the resilient test. Preferably millions of pulses should be applied to simulate real traffic. However, this would take inconveniently long time. Based on a few initial tests the following procedure presented in Table 3 were used:

Table 2 Resilient modulus loading procedure

Loading Sequence	Radial stress kPa	Deviatoric stress kPa			Number of load cycles
		Static	Dynamic	Total	
Conditioning	103.5	20.7	207	227.7	1000
1	20.7	4.1	10.4	14.5	100
	41.4	8.3	20.7	29.0	100
	69.0	13.8	34.5	48.3	100
	103.5	20.7	51.8	72.5	100
	138.0	27.6	69.0	96.6	100
2	20.7	4.1	20.7	24.8	100
	41.4	8.3	41.4	49.7	100
	69.0	13.8	69.0	82.8	100
	103.5	20.7	103.5	124.2	100
	138.0	27.6	138.0	165.6	100
3	20.7	4.1	41.4	45.5	100
	41.4	8.3	82.2	91.1	100
	69.0	13.8	138.0	151.8	100
	103.5	20.7	207.0	227.7	100
	138.0	27.6	276.0	303.6	100
4	20.7	4.1	62.1	66.2	100
	41.4	8.3	124.2	132.5	100
	69.0	13.8	207.0	220.8	100
	103.5	20.7	310.5	331.2	100
	138.0	27.6	414.0	441.6	100
5	20.7	4.1	103.5	108.6	100
	41.4	8.3	207.0	215.3	100
	69.0	13.8	345.0	358.8	100
	103.5	20.7	517.5	538.2	100
	138.0	27.6	690.0	717.6	100
6	20.7	4.1	144.9	149.0	100
	41.4	8.3	289.9	298.1	100
	69.0	13.8	483.0	496.8	100
	103.5	20.7	724.5	745.2	100
	138.0	27.6	966.0	993.6	100

Table 3 Permanent deformation loading procedure

Test number	Deviatoric stress kPa		Confining stress kPa	Stop criterion
	Min	Max		100 000 pulses or a strain of 4%
Test 1-2	4.7	345	20.7	
Tests 3 - 7	4.7	281	20.7	
Test 8,9,10	25.0	680	103.0	
Test 11 - 15	4.7	281	20.7	

4 MATERIAL MODELS

4.1 *Resilient modulus*

The elastic or resilient modulus of base course aggregates is determined in cyclic triaxial tests. Each loading cycle is performed at constant confining pressure tests. The resilient strain is taken as the unloading strain from maximum dynamic stress down to the static contact stress. The resilient modulus is then defined as:

$$M_r = \frac{\Delta\sigma_d}{\Delta\varepsilon_a^r} \qquad (1)$$

Where:

$\Delta\sigma_d$ = cyclic deviatoric stress
$\Delta\varepsilon^r_a$ = resilient axial strain

For base course aggregates the resilient modulus is typically dependent both on mean and deviatoric stress. An equation for modelling of this behaviour has been included in the AASHTO 2002 PDG model.

$$M_r = K_1\sigma_a\left(\frac{\theta}{\sigma_a}\right)^{K_2}\left(\frac{\tau_{oct}}{\sigma_a}+1\right)^{K_3} \qquad (2)$$

Where:

σ_a = reference stress (101 kPa)
θ = sum of principal stresses
τ_{oct} = octahedral shear stress
K_1, K_2 and K_3 are model parameters

The model parameters $K_{1\text{-}3}$ is determined by applying the method of least squared error to measured resilient modulus.

4.2 *Permanent deformation*

Several models have been proposed for predicting permanent deformation. These models are typically calibrated against repeated load triaxial tests. The development of permanent deformations in a road is hard to predict from laboratory tests since some important conditions can not be simulated in the triaxial apparatus. Triaxial tests may however be useful to study the relative difference between materials. The measurements from this project have been used to determine parameters for two different permanent deformation models.

Originally a two parameter model (a – *b* model) was proposed to be used in the 2002 PDG for prediction of permanent deformation

$$\varepsilon_p = \varepsilon_r \cdot a \cdot N^b \qquad (3)$$

Where:

ε_p = permanent axial strain
ε_r = resilient axial strain
N = number of pulses
a and b is model parameters

The parameters "a" and "b" are determined by curve fitting of the permanent strains measured in the permanent deformation part of the repeated load triaxial test. The resilient strains ε_r is calculated using the mean and shear stress in the loading procedure and the K_1, K_2 and K_3 parameters determined during the resilient modulus phase of the test.

A revised model for permanent deformation was however proposed for implemented in the 2002 PDG. The model was originally proposed by Tseng and Lytton /4/.

$$\delta_a(N) = \xi_1\left(\frac{\varepsilon_o}{\varepsilon_r}\right)e^{-\left(\frac{\rho}{N}\right)^{\xi_2\beta}}\varepsilon_v h \qquad (4)$$

where

δ_a = permanent deformation of a layer
N = number of traffic repetitions
$\varepsilon_o, \beta, \rho$ = material parameters
ε_r = resilient strain imposed in a laboratory test
ε_v = average vertical resilient strain in a layer
h = layer thickness
ξ_1, ξ_2 = field calibration functions

When interpreting the triaxial tests the field calibration functions ξ_1,ξ_2 are set to 1.0. A relationship dependent on water content W_c have been proposed for the parameters ρ and β. The base course aggregate used in these tests had a water content W_c = 3.6%.

$$\rho = 10^{(0.623+0.542 \cdot W_c)} = 373 \qquad (5)$$

$$\beta = 10^{(-0.6112-0.01764 \cdot W_c)} = 0.2115 \qquad (6)$$

Using the parameters predicted on basis of the water content did not give a good match with the observed behaviour. The parameters ρ and β can not be determined independently from a single data set due to the nature of the Tseng and Lytton equation.

In the data interpretation, the water content relationship was used to determine β while ρ was determined by curve fitting. In a triaxial test ε_v and ε_r are in principle the same variable. The ratio ($\varepsilon_o/\varepsilon_r$) was therefore treated as a variable to be calibrated in the triaxial test.

The resilient modulus test performed prior to the permanent deformation test results in 10 $^o/_{oo}$ initial strain. The resilient modulus loading procedure can not easily be converted to an equivalent number of load cycles in the permanent deformation test. To account for this initial deformation a N_{shift} parameter was introduced. The N_{shift} parameter was determined in a curve fitting procedure.

The Tseng and Lytton equation can then be simplified to:

$$\frac{\varepsilon_p}{\varepsilon_v} = \frac{\varepsilon_0}{\varepsilon_r} e^{-\left(\frac{\rho}{N+N_{shift}}\right)^{\beta}} \qquad (7)$$

5 RESULTS FROM TRIAXIAL TESTING

5.1 *Resilient modulus parameters*

Very small variations in resilient stiffness where observed between the different samples. No significant difference in resilient modulus between reinforced and unreinforced and between different products was found. The average values and standard deviations are given in Table 4.

Table 4 Average resilient stiffness parameters

	K1	K2	K3
Average for all tests	717	1.01	-0.59
Standard deviation	6.4 %	4.3 %	11.0 %

In Figure 3 both the measured and the calculated resilient modulus is plotted against mean stress with the parameters from the model fitting for test no. 7. The figure shows that the AASHTO equation (eq. 2) is able to reproduce the observed resilient stiffness very well for the triaxial stress condition. The scatter in the resilient stiffness is caused by the deviatoric stress dependency of the stiffness.

For comparison a mean stress dependent stiffness according to the equation below have been included on the figure. This shows that a reasonably good fit can be achieved also with a model not taking the deviatoric stress into account.

$$E_r = 3 \cdot (1 - 2 \cdot \nu) \cdot k_o \, \sigma_a \left(\frac{\sigma'_m + a}{\sigma_a} \right)^{1-n} \qquad (8)$$

Where

k_o = 1200
ν = 0.25
σ_a = 100 kPa
a = 0 kPa
n = 0.4

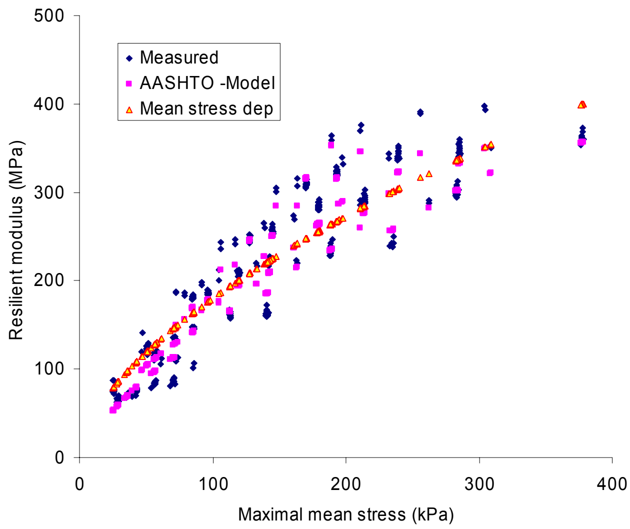

Figure 3 Measured resilient stiffness (test 7) compared with AASHTO model with average parameters for all tests.

5.2 *Permanent deformation*

The permanent deformation tests showed a relatively large scatter. The measured response for some of the tests is shown in Figure 4. Test 4, 12 and 15 were done with the same reinforcement product. Test 5 and 6 were done on a second product while test 7 and 13 were done on two different products.

As the results shows the difference between tests on one reinforcement product is larger than the average difference between products. On basis of these tests it is not possible to conclude that one reinforcement has a better reinforcing effect than the other. A significant difference was however found between the reinforced and the unreinforced samples. The average permanent deformation for reinforced and unreinforced samples is shown in Figure 5. Only comparable tests are used in the averaging, test 3 and 11 for unreinforced and test 4-7, 12, 13 and 15 for the reinforced. At 30 $^o/_{oo}$ permanent strain the average for the reinforced samples is 1530 cycles while the reinforced shows 220. This corresponds to a ratio of 7.

The large scatter is believed to be caused by small variations in properties for the samples. Small differences in behaviour for each load cycle may in the permanent deformation loading procedure be accumulated resulting in relatively large differences between the different samples.

Tests 8, 9 and 10, shown in, were performed with high confining pressures and high deviatoric stress (see Table 3). One of these tests, test 10, was not reinforced while tests 8 and 9 were reinforced. The unreinforced test 10 showed less deformation than tests 8 and 9, which may indicate that reinforcement do not have a significant effect for high confining pressures. Low reinforcement effect at high confinement stress is also reported by Moghaddas-Nejad & al 2003.

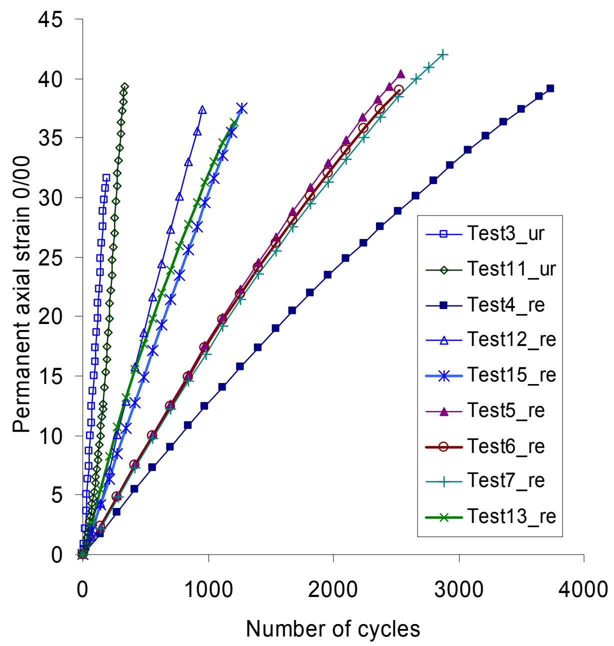

Figure 4 Permanent deformation at 20.7 kPa confining stress

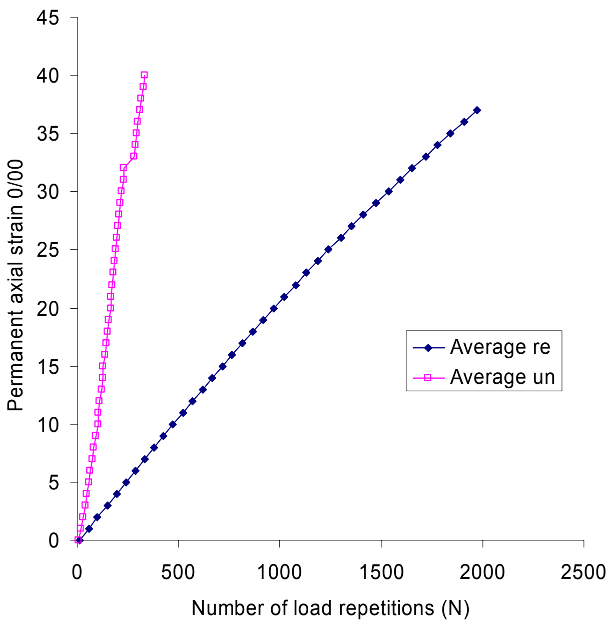

Figure 5 Average permanent deformation for reinforced and unreinforced tests.

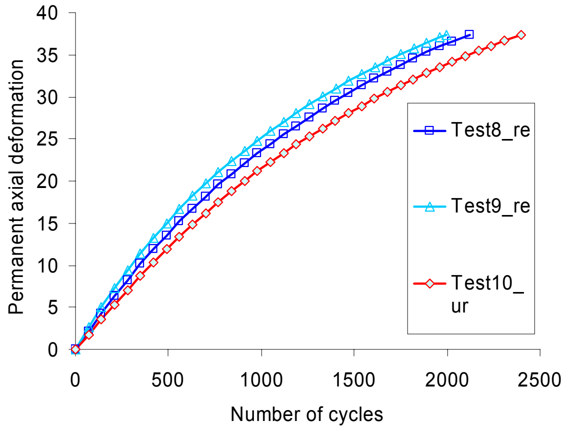

Figure 6 Permanent deformation at 103 kPa confining stress

The permanent deformation parameters determined for the average deformations Table 5 and Table 6 for the *a*-*b* and Tseng and Lytton models respectively. Due to differenses in stress conditions and some samples with strongly deviating results, the average values are calculated on basis of a selection of the tests. The N_{shift} values calculated in the curve fitting procedure is also included in the tables. The interpretation includes10 $^{o}/_{oo}$ strain from the resillient loading protocol as discussed in paragraph 4.2.

On basis on the average permanent deformation parameters extrapolated permanent deformation for a larger number of load cycles is calculated and presented in figure 7. Both permanent deformation models fits very well with the measured deformation, but the predicted strain at a large number of load repetitions show large deviation. This illustrates the problem with extrapolating the results from this type of tests. The permanent deformation models are strictly not valid for more load repetitions than the test data covers.

The validity of the permanent deformation model is also limited to the loading condition applied in the test. To be more useful models including dependency of the stress condition should be developed. A stress dependent model have been proposed by Moghaddas – Nejad (2003).

Table 5 Permanent deformation parameters- *a* - *b* model

Test type	*a*	*b*	N_{shift}
Unreinforced Test 3 and 11	0.206	0.821	30
Reinforced Test 4-7,13,15	0.061	0.776	280

Table 6 Permanent deformation parameters- Tseng and Lytton, β = 0.2115 for all tests.

Reinfor-cement	$\varepsilon_0/\varepsilon_r$	ρ	N_{shift}
Unreinforced Test 3, 11	3273	338010	65
Reinforced Test 4-7,13,12,15	2127	1363802	469

5.3 *Radial strain measurement*

The radial LVDT's where mounted on rings are placed with equal spacing on the sample with ring R1 at the top and R6 at the bottom. The reinforcement is placed in the middle of the sample between ring R3 and R4. A local restraining of the radial deformation should show less radial deformation for these rings. The distance between the rings is about 85 mm.

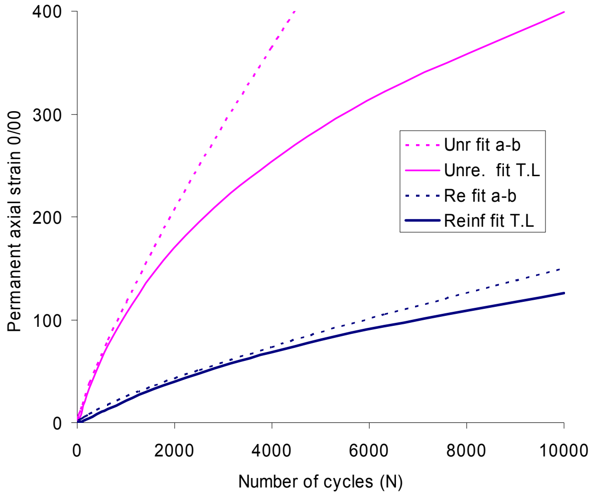

Figure 7 Permanent deformation prediction

Average permanent radial strain for all samples developed during the permanent deformation procedures for each LVDT is shown in Figure 8 for a reinforced and unreinforced test. For comparison purpose the strains are normalised (the reading for the individual rings are divided by the average for all six rings).

Ring R3 and R4 show significantly less deformation for the reinforced samples compared to the samples without reinforcement. The zone of influence for the reinforcement appears to reach about 100 mm above and below the reinforcement.

5.4 *Local measurement of vertical strain*

The local axial deformation sensors did not show any significant difference between the reinforced and unreinforced samples close to the reinforcement. The effect of the reinforcement is believed to be masked by the scatter caused by local movement of large particles. This was a problem for the sensors with the shortest measuring range.

6 CONCLUSIONS

The reinforcement is found to have no influence on the resilient stiffness of the triaxial samples. No significant difference in resilient stiffness is found between reinforced samples and samples without reinforcement.

No significant different in effect on permanent deformation is found for the different reinforcement types used in these tests.

A significant reduction in permanent deformation for the reinforced samples compared to the unreinforced samples is found. On average the reinforced samples reached to 7 times more load cycles at 30 $^{o}/_{oo}$ permanent strain.

The permanent deformations is more reduced by reinforcement at low radial stress (20 kPa), than at high radial stress (100 kPa).

The radial deformation sensors show a local effect of the reinforcement reducing the permanent radial deformation at the sensors closest to the reinforcement. The results indicate an influence zone extending about 100 mm above and below the reinforcement.

Parameters for two different permanent deformation models have been derived from the results. It is however a problem to extrapolate from to a larger number of load cycles covered in the tests. Both models fit well with the measurements but deviates when the number of load cycles exceeds the measurements. To be reliable, the permanent deformation models should be based on test data covering the entire number of load applications.

The validity of the permanent deformation model is also limited to the loading condition applied in the test. To be more useful models including dependency of the stress condition should be developed.

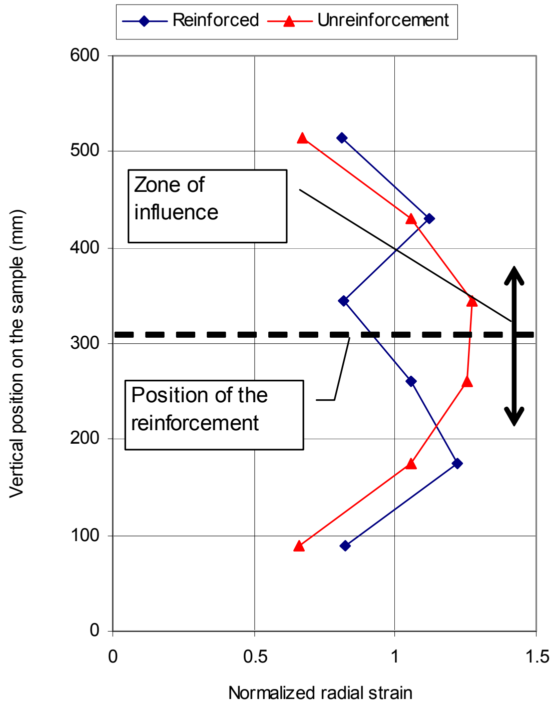

Figure 8 Measured radial strain

7 REFERENCE

Skoglund, Kjell Arne “A Study of Some Factors in Mechanistic Railway Track Design” Dr.ing. thesis, NTNU, Trondheim, March 2002.

Hoff, Inge “Material Properties of Unbound Aggregates for Pavement Structures” Dr.ing. thesis, NTNU, Tronheim, August 1999

CEN Unbound and hydraulic bound mixtures for roads – Test methods – Cyclic load triaxial tests CEN / TC 227 / WG 4 / TG 2

Tseng, K. and Lytton, R. “Prediction of Permanent Deformation in Flexible Pavement Materials”. ASTM STP 1016, 1989 , pp 154 – 172

Moghaddas-Nejad, Fereidoon and Small, John C. “Resilient and Permanent Characteristics of Reinforced Granular Material by Repeated Load Triaxial Tests”, Geotechical Testing Journal, Vol 26. pp 152-166. No. 2. May 2003.