Flexible Pavements, Gomes Correia (ed.) © 1996 Balkema, Rotterdam. ISBN 90 5410 523 2

Equipment and procedures for triaxial testing of subgrade soils

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ABSTRACT: One of the aims of the laboratory twinning project "A European Approach to Road Pavement Design" was to develop standard test procedures for repeated load triaxial testing of subgrade soils. For this purpose, repeatability tests were carried out to compare the triaxial equipment and test procedures of the four participating laboratories. This paper presents the results of these tests, and concludes by some recommendations for cyclic triaxial testing of subgrade soils.

1 INTRODUCTION

This paper presents studies performed at the beginning of the Science project "A European Approach to Road Pavement Design" to compare the equipment and test procedures used by the four laboratories participating to the project, for triaxial testing of subgrade soils.

The paper begins with a review of the test equipment used by each laboratory. Then, it presents a series of repeatability tests carried out on an artificial specimen and on two natural soils, Fontainebleau sand and London clay. Finally, the paper presents some recommendations for repeated load triaxial testing of subgrade soils, based on the experience of the participants, and on the results of the project.

2 TEST EQUIPMENT FOR SUBGRADE SOILS USED IN THE SCIENCE PROJECT

2.1 University of Nottingham

Principle

The University of Nottingham (UNOT) uses a servo hydraulic triaxial testing facility first developed in 1971 for testing of fine-grained soils and clays. Since 1971, it has undergone several modifications. The equipment is con-contained in an air conditioned laboratory, and includes a loading frame with two hydraulic actuators (for axial load and cell pressure), a triaxial cell, and an electronic data acquisition and control system, as illustrated on figure 1. With this apparatus, it is possible to cycle both the axial load and the confining pressure, to perform cyclic loadings following different stress paths.

The triaxial cell consists of an epoxy resin base, perspex side walls and an aluminium cell top. The specimen size is 76 mm in diameter by 150 mm in height. The fluid in the cell is silicon oil, and pressure is applied by connecting the hydraulic actuator to a piston acting on the silicone oil. The axial loading system has a load capacity of approximately 12 kN. Positive contact between the load ram and the top platen of the cell is ensured by vacuum, which allows to apply a negative deviator stress to the specimen (triaxial extension). The maximum cell pressure is 400 kPa.

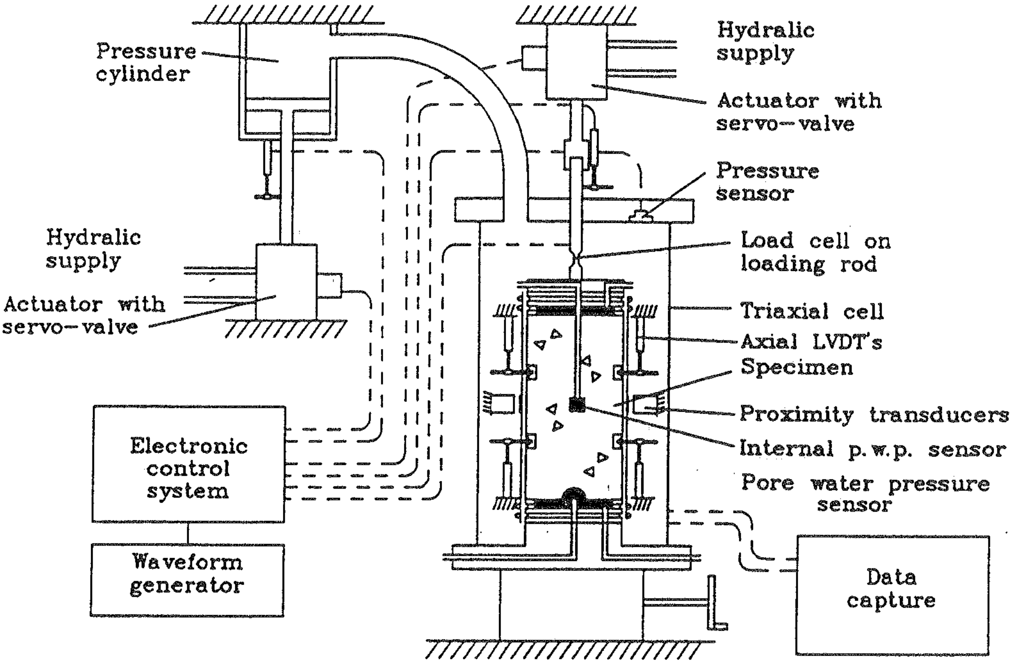

Fig. 1. Variable confining pressure triaxial apparatus of the University of Nottingham

Instrumentation

The transducers measuring the deformations of the specimen are attached to a metal support system attached to the cell base. Axial displacements are measured by four LVDTs, connected to the specimen using studs embedded in the soil. Radial deformations are measured by two proximity transducers, placed at midheight of the specimen (see figure 1). Pore pressures are measured through a porous stone secured to the cell base and, when needed, in the centre of the specimen, using a miniature pressure transducer. The following data is recorded in the tests:

- axial load and cell pressure;
- axial and radial deformations;
- specimen pore pressure and volume change.

2.2 Laboratorio Nacional de Engenharia Civil

For repeated load triaxial testing of soils, the Laboratorio Nacional de Engenharia Civil (LNEC) uses a triaxial apparatus for 75 mm × 150 mm specimens very similar to that of the University of Nottingham, and manufactured by the University. Some improvements have been made to volume measurement and suction control, however. This apparatus is shown on figure 2.

2.3 Laboratoire Régional des Ponts et Chaussées

Principle

The apparatus of the Laboratoire Régional des Ponts et Chaussées of Clermont-Ferrand (LRPC) uses a servo hydraulic loading system capable of cycling both the axial load and the cell pressure. The triaxial cell is a standard cell for 100 mm diameter specimens manufactured by Wykeham and Farrance. The base has been modified to accommodate 70 mm diameter specimens, and the extra space around the specimen is used to

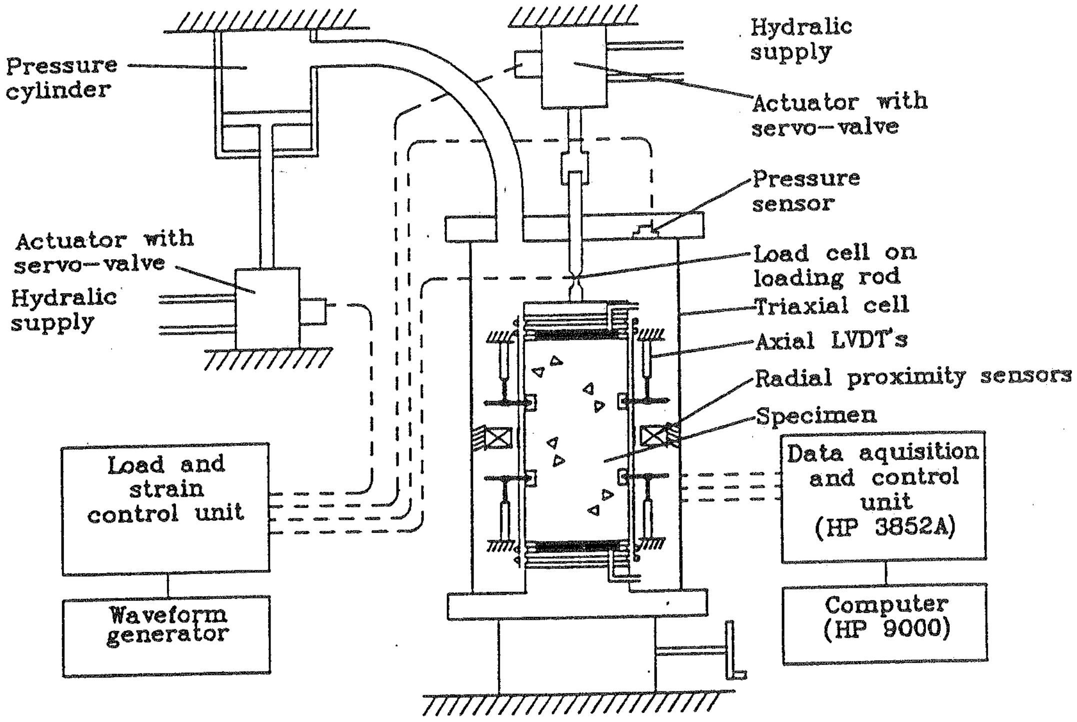

Fig.2. Variable confining pressure triaxial apparatus of the Laboratorio Nacional de Engenharia Civil

accommodate the transducers measuring locally the displacements of the specimen. The cell base has been modified to allow access for the cables of the instruments placed inside the cell. The confining fluid in the cell is silicon oil.

Instrumentation

The axial deformation of the specimen is measured using four LVDTs. Two LVDTs are placed at 1/4 of the height of the specimen, opposite each other, and two at 3/4 of the height of the specimen. Each LVDT is attached to the specimen by means of a stud embedded in the specimen.

The radial deformation is also measured by four LVDTs, two placed at 1/3 of the height of the specimen (opposite each other), and two at 2/3 of the height of the specimen. The core of each LVDT is terminated by a flat disc, 15 mm in diameter, which rests on a dome anchored in the specimen. The contact between the disc and the dome is ensured by a very light spring. This system allows the radial displacement to be measured accurately despite the axial deformations of the specimen.

The pore water pressure is measured using a DRUCK PDCR 22 pressure transducer working in tension and compression, mounted on the drainage network of the cell base. For a faster response time, a smaller DRUCK PDCR 81 transducer, (11.4 mm long and 6.4 mm in diameter), may be inserted directly into the middle of the specimen. The drainage system also allows to apply controlled values of suction to the specimen.

2.4 Delft University of Technology

Principle

The triaxial apparatus for soils of Delft University of Technology (DUT) is described on figure

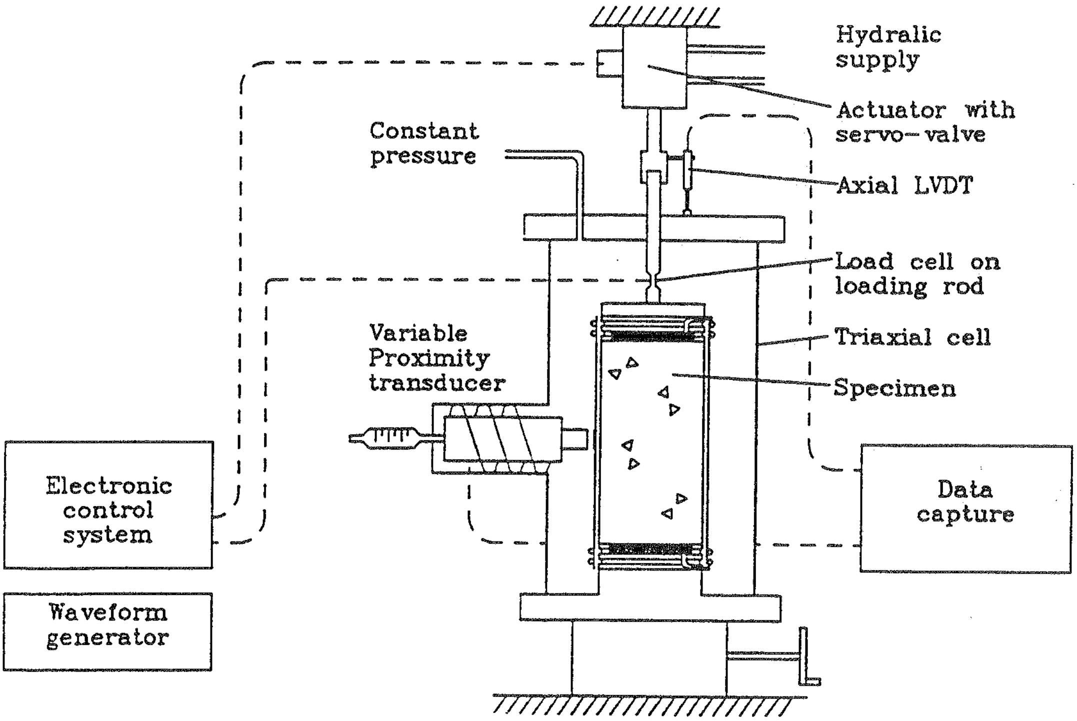

Fig. 3. Constant confining pressure triaxial apparatus of Delft University of Technology

3. This apparatus was developed for tests on fine-graded sands and laterites. The specimen size is 100 mm in diameter by 200 mm in height. The axial load is applied by means of a servo-hydraulic actuator. The cell pressure, which is constant in the tests, is applied by means of compressed air.

Instrumentation

The axial load is measured by a load cell placed inside the triaxial cell, to eliminate errors caused by friction between the loading piston and the upper part of the cell.

Axial deformation is measured by an LVDT connected to the loading piston, outside the triaxial cell. The advantage of this solution is that the transducer can be adjusted during the test; This allows to use an LVDT of smaller range, with a better accuracy. Radial deformation of the specimen is measured by 3 proximity transducers, attached to the Plexiglas cell, at half the specimen height (see figure 3).

The suction of the specimen may be measured by a tensiometer, consisting of a ceramic tip inserted in the specimen, near the upper platen, connected with a pressure transducer located outside the cell.

3 PRELIMINARY TEST PROGRAMMES OF THE SCIENCE PROJECT

3.1 First test programme

At the beginning of the Science project, before starting detailed experimental studies on various materials, it was decided to perform a series of preliminary tests, to compare the test methods and test equipment of the four participating laboratories. These comparative tests were conducted on both unbound granular materials and subgrade soils. The tests on granular materials are described in another paper presented to this conference. For the tests on soils, presented hereafter, two materials were chosen: Fontainebleau sand, which was tested dry, and London clay, which was tested in partially saturated conditions.

The test procedure was identical for the two materials, and included 5 stages:

1. A consolidation under a confining pressure $p_0 = 15$ kPa.
2. A cyclic preloading (conditioning), consisting of 200 cycles with a cyclic deviator stress $q_r = 0.5.q_{failure}$, and a cyclic stress ratio $q_r/p_r = 3$ ($q_r = \sigma_{1r} - \sigma_{3r}$ and $p_r = (\sigma_{1r} + 2\sigma_{3r}) / 3$).
3. Several short cyclic loadings, of 50 cycles each, following different stress paths, with cyclic stress ratios q_r/p_r of 3, 2.5, 2, 1.5, 1, 0.5 and 0. These loadings were used to determine the resilient (elastic) properties of the soils.
4. A sequence of loading with a large number of cycles (10^5), with a static confining pressure $p_0 = 60$ kPa, a cyclic deviator stress $q_r = 0.5.q_{failure}$, and a cyclic stress ratio $q_r/p_r = 3$.
5. Finally, the determination of the shear strength of the soil, for a confining pressure $p_0 = 60$ kPa.

Each laboratory performed one test on Fontainebleau sand, and one test on London clay. The results of these tests will not be presented in detail, because they were very scattered. The following conclusions were drawn from this first test programme:

- All the laboratories did not follow exactly the test procedure, due to differences in their test equipment: for example, some laboratories could not perform loadings with a cyclic variation of the confining pressure.
- For the clay, some laboratories had difficulties with obtaining the specified water content.
- The number of cycles of conditioning was not sufficient to stabilise the permanent strains of the specimen, and obtain a really elastic behaviour in stage (3)
- The differences between the results of the 4 laboratories were quite large. This was attributed to differences in the test procedures.
- The number of tests was too limited (only one test per laboratory for each material) to perform any statistical analysis of the results.

After this first test programme, it appeared necessary to study in detail the repeatability of these triaxial tests. Two experimental studies were carried out for that purpose:

- A series of tests on an artificial specimen of known mechanical properties.
- A second programme of comparative tests, limited to one soil (London clay). but including a larger number of tests.

3.2 Tests on artificial specimen

Objectives and test procedure

Because of the large scatter obtained in the first test programme, before starting other tests on soils, it was decided to verify the equipment of each laboratory, and especially the accuracy of the instrumentation used for strain measurement. For this purpose, a test programme using an artificial, synthetic, specimen was set up. This programme concerned both the equipment used for subgrade soils and for unbound granular materials. The results presented here concern only the equipment for soils.

The specimen used for this programme was made of polytetrafluorethylene (PTFE), and had an elastic modulus of approximately 70 MPa. The initial size of this specimen was 160 mm in diameter by 320 mm in height, but this size had to be reduced several times, to adapt it to the apparatus used by each laboratory.

The test procedure included a series of 3 loadings, presented in table 1. Because of the viscoelastic behaviour of the specimen, only static loadings were used.

Results

The apparatus tested with the artificial specimen included:

- the apparatus for 100×200 mm specimens of Delft University of Technology (DUT);
- the apparatus for 76×144 mm specimens of Nottingham University (UNOT);
- the apparatus for 76×144 mm specimens of the Laboratorio Nacional de Engenharia Civil (LNEC);

- the apparatus for 70×140 mm specimens of the Laboratoire Régional des Ponts et Chaussées of Clermont-Ferrand (LRPC).

The results of LRPC will not be presented, because this laboratory did not respect the loading procedure.

Table 1. Loading procedure used for the tests on the artificial specimen

Loading	Stresses		Duration
	σ_3 kPa	q kPa	seconds
1 Loading	250	0	3600
Unloading	0	0	3600
2 Loading	250	375	3600
Unloading	0	0	3600
3 Loading	100	600	3600
Unloading	0	0	3600

Table 2 presents the axial and radial strains (ε_1 and ε_3) obtained by the different laboratories for the second an third loadings, and also the values of the elastic modulus and Poisson's ratio corresponding to these strains. (the first loading produced only extremely small strains, and so its results are not significant).

Table 2: Results of the tests on the artificial specimen

Loading	Lab	Strains		Elastic parameters	
		ε_1 $\mu\varepsilon$	ε_3 $\mu\varepsilon$	E MPa	ν
2	LNEC	6857	-3339	71	0.49
	UNOT	10828	-3680	49	0.44
	DUT	6732	-3248	70	0.49
3	LNEC	10328	-5542	64	0.53
	UNOT	14861	-6092	50	0.44
	DUT	10517	-5640	61	0.52

The results are similar for the 2 loadings:

- For axial strains, LNEC and DUT obtain results which differ by less than 2%. UNOT, however, obtains much higher values of ε_1 than the two other laboratories.
- For radial strains, the results of LNEC and DUT are again in very good agreement (they differ by less than 3 %). The values of UNOT are about 10 % higher.

From these results, it was concluded that the measurements of axial and radial strains made at LNEC and DUT were reliable (differing by no more than 2 or 3 %). At UNOT however, there was a serious problem with the measurement of axial strains.

3.3 Second test programme

Objectives

The objective of this second test programme was to study in detail, for one particular soil, the reproductibility of these repeated load triaxial tests. The material selected for this programme was London clay. It was tested in the following conditions:

- water content: 36 % (optimum water content of standard Proctor test)
- dry density: 1370 kg/m^3 (maximum density of standard Proctor test)

Each laboratory used its own test equipment. The test procedure included two parts:

- A cyclic preloading, consisting of 100000 identical load cycles.
- A series of short cyclic loadings, used to determine the resilient behaviour of the material for different levels of stress.

. The analysis of the results focused on:

- The permanent axial and radial strains (ε_{1p} and ε_{3p}) recorded during the conditioning.
- The resilient axial and radial strains (ε_{1r} and ε_{3r}), and also the resilient modulus Mr (secant modulus of elasticity) obtained for each short loading.

Test procedure

For the preparation of the specimens, each laboratory used its own equipment:

- At UNOT, the clay was compacted in five layers, using a Proctor hammer. Only half the height of the hammer was used, but with twice the standard number of blows.

- At LNEC, the clay was compacted by the standard Proctor compaction method. Because of the reduced size of the specimen (76×144 mm), the material was compacted in five layers, with respectively 10, 10, 10, 11 and 11 blows of the Proctor hammer.
- At LRPC, the clay was compacted in five layers. Each layer was compacted by applying six blows of a small hammer having a diameter of 35.5 mm and a weight of 1288 g.
- At DUT, the specimen was built in six layers, using a special tamping device, developed to compact the soil without damaging the membrane mounted inside the compaction mould. the surface of each compacted layer was scarified to ensure a good contact between the layers.

The loading procedure is described in table 3. It included:

1. 100000 cycles of preloading (conditioning), with an initial static confining pressure $p_0 = 60$ kPa and cyclic stresses $p_r = 20$ kPa and $q_r = 60$ kPa. During this preloading, the resilient and permanent strains of the specimen were recorded at N = 20, 50, 100, 200, 400, 1000, 2500, 5000, 10000, 25000, 50000, 75000 and 100000 cycles.
2. series of 12 cyclic loadings, of 100 cycles each, with different stress levels, and with a cyclic stress ratio $q_r/p_r = 3$; loadings with other stress ratios were excluded, because they could not be performed by all the participants. During these loadings, the axial and radial strains of the specimen were recorded during the last cycle.

All the loadings were performed in undrained conditions, and at a frequency of 1 Hz.

Each laboratory was to perform 3 identical tests, following the procedure of table 3. However, LNEC and UNOT performed 3 additional tests. The characteristics of the specimens tested in each laboratory are given in table 4.

Permanent strains

Figure 4 presents the results obtained by 3 laboratories (UNOT, LRPC and DUT) for the permanent axial strains. In the 4th laboratory, LNEC, the permanent strains were not recorded.

Table 3: Loading procedure of the second test programme

Loading	Number of cycles N	Stresses			
		p_0 kPa	p_r kPa	q_r kPa	q_r/p_r
1.*	100000	60	20	60	3
2.	100	15	5	15	3
3.	100	15	10	30	3
4.	100	30	5	15	3
5.	100	30	10	30	3
6.	100	30	15	45	3
7.	100	45	5	15	3
8.	100	45	10	30	3
9.	100	45	15	45	3
10.	100	45	20	60	3

* Specimen conditioning

Table 4: Characteristics of tested specimens

Lab	Test	Specimen size	w %	γ_d kg/m^3
LNEC	1	76*144 mm	36.0	1380
	2	76*144 mm	36.5	1370
	3	76*144 mm	35.7	1380
	4	76*144 mm	35.6	1370
	5	76*144 mm	35.5	1370
	6	76*144 mm	36.8	1370
UNOT	1	76*144 mm	36.0	-
	2	76*144 mm	36.0	-
	3	76*144 mm	36.0	-
	4	76*144 mm	35.9	1220
	5	76*144 mm	35.2	1240
	6	76*144 mm	36.3	1220
LRPC	1	70*140 mm	36.0	1368
	2	70*140 mm	36.0	1368
	3	70*140 mm	34.4	1388
DUT	1	102*207 mm	36.7	-
	2	102*213 mm	36.2	-
	3	102*211 mm	36.7	-

These results are also presented in table 5, which indicates:

- The values of the permanent axial and radial strains (ε_{1p} and ε_{3p}) obtained in each test at the end of the conditioning (at 100000 cycles).
- The means, standard deviations and coefficients of variation (standard deviation divided

by mean) of the results of each laboratory.

For permanent axial strains, UNOT and DUT obtain similar results, with mean values of e_{1p} of about 200.10^{-4}, and coefficients of variation of about 20 %. LRPC, on the contrary, obtains only very small permanent axial strains, about 60 times smaller than the other laboratories.

For permanent radial strains, there are large differences between the mean values of ε_{3p} obtained by the 3 laboratories, and the scatter of the results of each laboratory is also important, with coefficients of variation of about 20 % to 40 %. Again, LRPC obtains extremely small strains in comparison with the other laboratories.

Resilient strains

Figures 5 and 6 present the results obtained by all the laboratories for resilient axial and radial strains, for loadings with a confining pressure p_0 = 30 kPa and with different cyclic deviator stresses q_r. The overall scatter of the results is large, and similar for ε_{1r} and for ε_{3r}.

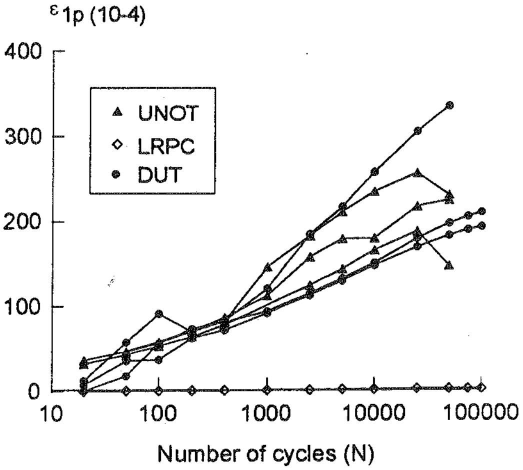

Fig. 4. Variation of permanent axial strains with the number of cycles

Table 5: Permanent axial and radial strains at the end of the conditioning (at 100000 cycles).

	Permanent axial strain ε_{1p} (in 10^{-4})			Permanent radial strain ε_{3p} (in 10^{-4})		
	UNOT	LRPC	DUT	UNOT	LRPC	DUT
1	148	3.5	335	-31.5	-1.2	-212
2	231	3.5	194	-105	-1.9	-109
3	225	3.6	211	-85.3	-1.3	-138
$\bar{x}$	201	3.5	247	-73.8	-1.5	-153
s	37.9	0.0	63.1	31	0.3	43.6
$s/\bar{x}$	18.8 %	1.3 %	25.6 %	41.9 %	21.1 %	28.5 %

1, 2, 3 : results of individual tests
$\bar{x}$: mean, s:standard deviation

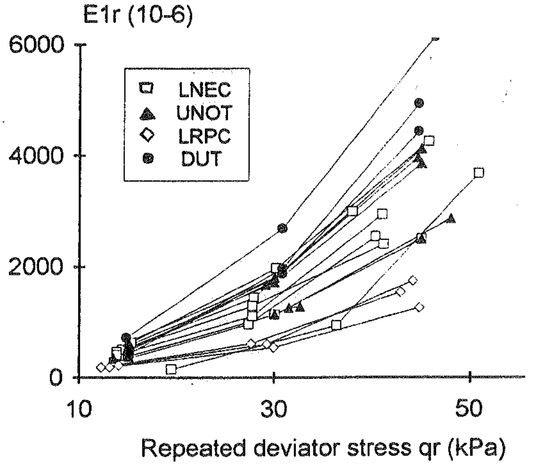

Fig. 5. Resilient axial strains obtained for the loadings with p_0 = 30 kPa

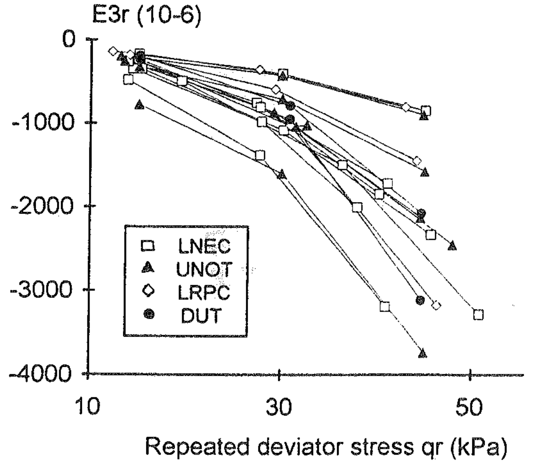

Fig. 6. Resilient radial strains obtained for the loadings with p_0 = 30 kPa

Table 6: Scatter of resilient axial strains (loadings with $p_0 = 30$ kPa)

RESILIENT AXIAL STRAIN ε_{1r} (values in μstrains)

	LNEC			UNOT		
	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa	q_r=15 kPa	q_r=30 kPa	q_r= 45 kPa
$\bar{x}$	404	1287	3136	494	1517	3465
s	155	356	645	126	269	651
$s/\bar{x}$	38.3 %	27.7 %	20.6 %	25.6 %	17.7 %	18.8 %

RESILIENT AXIAL STRAIN ε_{1r} (values in μstrains)

	LRPC			DUT		
	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa
$\bar{x}$	202	593	1514	549	2180	5173
s	13.4	31.6	200	122	366	719
$s/\bar{x}$	6.7 %	5.3 %	13.2 %	22.2 %	16.8 %	13.9 %

$\bar{x}$: mean, s:standard deviation

Table 7: Scatter of resilient radial strains (loadings with $p_0 = 30$ kPa)

RESILIENT RADIAL STRAIN ε_{3r} (values in μstrains)

	LNEC			UNOT		
	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa
$\bar{x}$	-356	-1082	-2396	-379	-921	-2147
s	104	276	623	234	397	960
$s/\bar{x}$	29.2 %	25.5 %	26 %	61.6 %	43.1 %	44.7 %

RESILIENT RADIAL STRAIN ε_{3r} (values in μstrains)

	LRPC			DUT		
	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa
$\bar{x}$	-171	-456	-1049	-226	-921	-2789
s	22.9	99.2	284	25.6	99.7	502
$s/\bar{x}$	13.4 %	21.8 %	27.1 %	11.3 %	10.8 %	18 %

$\bar{x}$: mean, s:standard deviation

The same results are also summarised in tables 6 and 7, which indicate:

- the mean values of ε_{1r} and ε_{3r} obtained by each laboratory, for each stress path (each q_r).
- the standard deviations and coefficients of variation of the results of each laboratory, which reflect the scatter of the results of each laboratory.

For resilient axial strains, table 6 shows that:

- Only two laboratories, LNEC and UNOT obtain similar mean values of ε_{1r}. DUT obtains larger values than these two laboratories; this is probably due to fact that at DUT, (and only there), the axial strain is measured with a transducer placed outside the triaxial cell, following the movements of the cell piston, as it is well known that this method tends to overestimate the strains of the specimen. The reason why LRPC obtains about 2 times smaller values of ε_{1p} than LNEC and UNOT is not clear.
- The smallest scatter is obtained at LRPC, with coefficients of variation of variation of about 5% to 13%. The largest scatter is observed at LNEC, with coefficients of variation of about 20 % to 40 %.

For resilient radial strains, the following conclusions can be made (see table 7):

- LNEC, UNOT and DUT, which all use proximity transducers for measuring radial strains, obtain mean values of ε_{3r} which are in good agreement. LRPC, however, obtains systematically about 2 times smaller values of ε_{3r} than the other laboratories.
- The scatter of the results is even larger than for axial strains: the lowest scatter is obtained at DUT, with coefficients of variation of about 10 % to 18 %; this seems logical, because DUT uses somewhat larger specimens (100 mm in diameter) than the other laboratories The largest scatter is obtained at UNOT, with coefficients of variation exceeding 40 %.

Resilient modulus Mr

It seemed useful to examine as well the repeatability obtained for the resilient modulus $M_r = q_r/\varepsilon_{1r}$. The results obtained for M_r are presented in table 8.

Table 8: Scatter of resilient moduli (loadings with $p_0 = 30$ kPa)

RESILIENT MODULUS M_r (values in MPa)						
	LNEC			UNOT		
	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa
$\bar{x}$	33.2	24.6	14	31.4	20.6	13.7
s	8.5	7.5	2.1	7.1	4.3	3
$s/\bar{x}$	25.5 %	30.5 %	14.7 %	22.5 %	20.7 %	21.9 %

RESILIENT MODULUS M_r (values in MPa)						
	LRPC			DUT		
	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa	q_r=15 kPa	q_r=30 kPa	q_r=45 kPa
$\bar{x}$	64.9	48.9	29.6	28.6	14.5	8.9
s	2.1	4.2	4.4	5.9	2.2	1.0
$s/\bar{x}$	3.3 %	8.7 %	14.9 %	20.7 %	15.2 %	11.7 %

$\bar{x}$: mean, s:standard deviation

The results obtained for Mr are not very different from those obtained for ε_{1r}:

- LNEC, UNOT and DUT obtain mean values of M_r which are similar. LRPC obtains, for all stress levels, values of M_r which are about 2 times higher.
- Typical standard deviations obtained for M_r are of the order of 2 to 6 MPa. This gives an indication of the accuracy with which the resilient modulus of a soil can be determined.
- The results of all laboratories indicate that the resilient modulus of the clay decreases significantly as the deviator stress increases.

Conclusions

The tests have shown that different laboratories, using the same loading procedure, but different equipment, and different methods of preparation of specimens, can obtain entirely different values of permanent strains. The same conclusion was also made for granular materials (see Paute, Dawson and Galjaard (1993)). This is probably due to the fact that permanent strains are largely affected by any previous loading of the specimen, including of course the loading due to compaction.

These results raise some doubts about the significance of the permanent strains obtained in repeated load triaxial tests. For this reason, it would be interesting to make comparisons between the permanent strains obtained in laboratory tests and those obtained in the field, in a pavement subgrade submitted to real traffic.

For resilient strains, one laboratory, LRPC, obtained systematically about 2 times lower axial and radial strains than the other laboratories. The cause of these large differences was not found.

For the three other laboratories (LNEC, UNOT and DUT), the following conclusions could be made:

- DUT obtained larger mean values of ε_{1r} than LNEC and UNOT (which obtained similar values), and this was attributed to the fact that the system used by DUT for measuring axial strains (a transducer placed outside the triaxial cell) tends to overestimate the strains of the specimen
- For radial strains, there were no systematic differences between the results of the 3 laboratories.
- In each laboratory, the scatter was important, with coefficients of variation of ε_{1r} and ε_{3r} frequently exceeding 20 %. For radial strains, the best repeatability was obtained at DUT, where the specimens were larger than in the other laboratories (100 mm in diameter instead of 76 mm).

All these results show that these repeated load triaxial tests are difficult to perform, and that their results are affected by serious scatter.

4 RECOMMENDATIONS FOR REPEATED LOAD TRIAXIAL TESTING OF SUBGRADE SOILS

4.1 Introduction

One of the major advantages of a joint-venture project such as this Science project is the possibility of exchange of expertise, technology and experience between the different partners. It seemed important to present here some recommendations for repeated load triaxial testing of subgrade soils, resulting from these exchanges, and from the results obtained during the project.

The recommendations presented hereafter concern mainly fine-grained, cohesive soils. As for cohesionless soils, their behaviour is very similar to that of unbound granular materials, and most of the recommendations proposed for granular materials in the paper presented to this conference by Paute, Dawson and Galjaard (1993) are also applicable to cohesionless soils.

4.2 Factors affecting the behaviour of fine-grained subgrade soils

The cyclic behaviour of fine-grained soils presents some important differences with the behaviour of unbound granular materials, which must be taken into account in the test procedures used for these materials:

(1) The cyclic behaviour of fine-grained soils is largely affected by the build up of pore pressures. This build up is observed even in drained conditions, because the low permeability of these materials does not allow the specimen to drain completely during cyclic loading. These pore pressures tend to reduce the stiffness of the materials, and can even cause failure.

(2) Because of their low permeability, partially saturated fine-grained soils can develop high levels of suction, which can increase considerably their stiffness. For this reason, measurement of suction seems essential for understanding the behaviour of specimens of fine-grained soils.

(3) The behaviour of cohesive soils is very sensitive to stress history. For this reason, the response of these soils in repeated load triaxial tests can be greatly affected by the initial conditioning of the specimens, and by the order in which the different stress paths are applied.

(4) The cyclic behaviour of fine grained soils is sensitive to loading frequency.

4.3 Test equipment

General characteristics

Testing of cohesive subgrade soils requires more flexible equipment than testing of unbound granular materials: because fine-grained soils are sensitive to frequency and wave form, relatively high loading frequencies, representative of those produced by road traffic (1 Hz or more) must be applied, and the shape of the load signal must be well controlled; the possibility of applying complex load signals (with rest periods allowing drainage, for example) is also useful. For this reason, servo-controlled hydraulic loading systems seem best suited for testing of subgrade soils. (It is the choice adopted by all the laboratories participating to the Science project).

When the purpose of the tests is to develop constitutive models, which are to be used for finite element calculations (as was the case in this project), it is highly recommended to use equipment capable of applying cyclic cell pressures, and thus cyclic loadings along a large variety of stress paths. For more routine tests, (determination of elastic modului, for routine pavement design, or for material classification, etc..), constant cell pressure may be sufficient.

The repeatability tests performed in this project (test programme 2) have shown that repeated load triaxial tests on soils are affected by serious scatter. For this reason, a specimen size of 75 mm in diameter (and twice that height) seems a minimum to obtain reasonably accurate results; 100 mm seems even preferable, according to the conclusions of the second test programme.

Instrumentation

Because of the small level of the resilient strains of the specimens, (about 100 to 1000 μstrains), very accurate measurement of axial and radial strains is essential in these tests. For this reason, the strains should be measured directly on the specimen, in the central part to avoid end-effects. And for better representativity, several transducers should be used for each measurement, (3 axial transducers and 3 radial transducers seems a good solution), and their readings should be recorded separately.

For measurement of axial strains, 3 of the laboratories involved in the Science project use a set of 4 linear variable differential transformers (LVDTs), connected to 4 studs embedded in the specimen, 2 placed at 1/4 of the height of the specimen, and 2 placed at 3/4 of the height of the specimen, and this system gives satisfactory results.

For the measurement of radial strains, 3 of the laboratories of the Science project use proximity transducers (2 or 3, placed horizontally at mid-height of the specimen), and the tests on the artificial specimen have shown that this solution gives good results. The major advantage of proximity transducers, when working with relatively small and soft soil specimens, is that the specimen is not disturbed in any way, as there is no contact between the specimen and the transducer.

As already mentioned, when testing partially saturated soils, it is important to measure specimen suction. For that purpose, several laboratories of the Science project use tensiometers, consisting of a small porous ceramic tip, inserted directly in the specimen, connected with a pore pressure transducer, placed either inside or outside the triaxial cell. Such tensiometers are limited to suctions lower than 100 kPa (even 80 or 90 kPa in practice), and cannot be used for measuring cyclic pore pressures, because they have a relatively long response time.

As transducer accuracy plays a critical role in these tests, these transducers must be checked and calibrated frequently. It is also recommended to use a synthetic specimen of known mechanical properties (with a stiffness similar to that of subgrade soils) to check periodically the entire apparatus.

4.4 Preparation of specimens

For unbound granular materials, the influence of the method of preparation of the specimens was studied in detail in this project, (see the article presented to this conference by Paute, Dawson and Galjaard) and it was found that the quality of the compaction of the specimens affects greatly the results of repeated load triaxial tests. For subgrade soils, similar studies were not performed, but the quality of the specimens is certainly equally important for soils. For this reason, it is recommended to use well-tried, reliable compaction methods for the preparation of specimens of subgrade soils. The following methods, can be proposed:

- For dry, cohesionless soils, good quality specimens can be obtained by pluviation, a method which consist in letting the material fall into a mold from a specified height, through a grid to ensure a homogeneous distribution.
- For materials with a small cohesion, the LRPC of Saint-Brieuc has obtained very good results with the vibro-compression method developed for unbound granular materials (presented in the paper of Paute, Dawson and Galjaard (1993)). In this method, the material is compacted in one layer, under the simultaneous action of a horizontal vibration and a small axial compressive load.
- For cohesive soils, the specimens can be consolidated from a slurry; then, if the specimens are to be tested in partially saturated conditions, their water content must be lowered by subjecting them to negative pore water pressures. (This method is used by the University of Nottingham). This method ensures very good results, but is reserved for research purposes, because it is very time-consuming. A more practical, faster, method consists in compacting the specimen in several layers by static compression from both ends.

4.5 Test procedures for subgrade soils

Test specimen conditions

In the field, subgrade soils are generally partially saturated, and laboratory tests should be performed in the same conditions, (with measurement of suction). Two methods can be used for preparing partially saturated specimens:

- The first method consists in preparing and compacting the specimen at a given water-content, and then measuring the suction in the specimen with a tensiometer, and testing the specimen in this condition.

- The second method consists in starting with a saturated specimen, and then submitting it to a controlled suction through the drainage system of the cell and allowing it to reach drained equilibrium under this suction.

The advantage of the second method is that the specimen can be tested at precise, controlled, suction levels. However, for soils of low permeability, the time needed to reach drained equilibrium can be extremely long (several weeks to several months). For this reason, in this project, it is the first method which was adopted, and it is believed that this method is suitable for most purposes.

To simulate the field conditions, where the subgrade soil is subjected to a small overburden pressure, the specimens should be consolidated under a cell pressure of about 10 to 20 kPa before applying the cyclic loadings.

As for drainage conditions, in this project, cyclic loadings were applied in undrained conditions, and it is believed that this corresponds well to in situ conditions. Moreover, no pore pressure measurements were made during the cyclic loadings, and the results of the tests were interpreted in terms of total stresses.

Examples of test procedures

Finally, we present here the loading procedures adopted for the "third test programme" of the Science project. They represent the final test procedures adopted in the project, and take into account the conclusions of the repeatability tests and of the tests on the artificial specimen. Two test procedures are presented: one for the study of resilient (elastic) behaviour, and one for the study of permanent strains.

All the tests were performed as follows:

1. The soils were tested at degrees of saturation of 70 %, 80 % and 90 %, and at densities close to the maximum dry density of the Normal Proctor test, which represent well conditions found in subgrade soils in Europe.

2. Because serious scatter was observed in the previous tests programmes, it was decided to repeat each test twice.

3. The cyclic loadings were carried in undrained conditions and the wave form used was a haversine with 1 second loading and 1 second rest period.

4. For the tests used to study the resilient behaviour, it was recognised as essential to perform a cyclic conditioning, including a large number of cycles, before determining the resilient behaviour. The role of this conditioning is to stabilise the permanent strains of the specimen, and bring the specimen into a state where its behaviour is essentially elastic.

Procedure for the study of resilient behaviour

The loading procedure adopted to study the resilient behaviour is the following:

1. Apply a confining pressure of 10 kPa, and allow time for strain stabilisation (axial or radial deformation of less than 10 $\mu\varepsilon$ / minute).

2. Conditioning: Apply 80000 cycles of a deviator stress that is 60 % of the expected failure value. Record the stresses and strains of the specimen, and the pore water pressure (if possible), at the following numbers of cycles: 10, 20, 50, 100, 200, 400, 1000, 2500, 5000, 7500, 10000, 15000, 20000, 40000, 60000 and 80000.

3. Keep the confining pressure at 10 kPa and allow time for strain stabilisation.

4. Apply 50 cycles of vertical stress and confining pressure (in phase) for each of the following combinations: cyclic deviator stresses $q_r = 20$, 40, 60 and 80 kPa, and cyclic stress ratios $q_r/p_r = 3$ and 1.5. Never exceed 50 % of the deviator stress at failure. Begin always with the loadings with $q_r/p_r = 3$, and with the maximum value of q_r. For each sequence, record the stresses and strains of the specimen, and the pore water pressure (if possible), at cycles number 49 and 50.

5. Raise the confining pressure to 30 kPa and allow time for strain stabilisation

6. Repeat step n° 4

7. Raise the confining pressure to 45 kPa and allow time for strain stabilisation.

8. Repeat step N° 4

Procedure for the study of permanent strains

The study of permanent strains includes 6 tests, performed with the different stress paths indicated in table 9.

Each test consists in applying 80000 cycles of loading, and measuring the stresses and strains of the specimen and the pore water pressures (if possible) at the following numbers of cycles: 10, 20, 50, 100, 200, 400, 1000, 2500, 5000, 7500, 10000, 15000, 20000, 40000, 60000 and 80000 cycles.

Table 9: Stress paths used for the study of permanent strains

Consolidation pressure σ_3 (kpa)	Cyclic deviator stress q_r (kpa)
10	$0.65 \times q_f$
10	$0.50 \times q_f$
10	$0.35 \times q_f$
30	$0.65 \times q_f$
30	$0.50 \times q_f$
30	$0.35 \times q_f$