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A large triaxial apparatus for the study of granular materials under repeated loading used at LNEC

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ABSTRACT: The improvement of analytical road pavement and railway infrastructure design methods requires a rational study of the mechanical behaviour of the constituent materials. The repeated load triaxial apparatus is one of the most common and useful tools for determining the parameters used in these design methods. This paper presents a description of a repeated load triaxial apparatus designed to test unbound granular materials of up to 0/60 gradings. The importance of the compacted density in the behaviour of these materials necessitates a laboratory compaction method that reproduces the in-situ conditions. Consequently a method of compaction and control of the density is also presented. By using this apparatus the most common parameters used in analytical pavement design (resilient modulus and Poisson's ratio) are acquired. This is illustrated by testing a 0/20 graded crushed granite used as base course for road construction. This test apparatus may also be used to investigate the permanent deformation characteristics of base course materials.

1 INTRODUCTION

Unbound granular materials play an important role in railway infrastructures and flexible pavements where they are often used in base and subbase layers. It is important to determine the mechanical behaviour of these materials for use in analytical design methods. This study needs to be done at a laboratory level on the selected materials before they are used in the construction. In a rational study the laboratory equipment must simulate the environmental and loading conditions to which the material is to be subjected both during and after construction. From a mechanistic point of view it is necessary to apply a well defined stress state and measure the deformations accurately.

The simulation of railway and road loading conditions in a laboratory is complex. Consider an element of unbound granular material in a pavement structure and a wheel load some distance laterially from the element. The stress applied on the element comprises of two components namely shear stress and normal stress. To start with the horizontal shear stress is the major stress component, however as the wheel approaches a position above the element the horizontal shear stress lessens and the vertical and horizontal normal stresses become dominant, at the instant when the wheel load is located right above the element the horizontal shear stress disappears.

Therefore during the passage of a wheel load over an element in a pavement system there is a stress change from shear to triaxial loading and back to shear again. Thus since the triaxial apparatus can only apply normal loading this apparatus is a compromise to the true loading situation.

This report described the various features of a repeated load large triaxial apparatus for research work involving base course materials used for railway and road pavement construction.

A triaxial specimen of 600mm height and 300mm diameter may be tested using this apparatus as originally described by Nunes and Gomes Correia (1991a) and conceptually based on a triaxial cell used for testing rockfills by Veiga Pinto (1983). Recently however, by using instrumentation attached directly to the specimen, more accurate measurement of the axial and radial deformations has been achieved.

The specimens are prepared by vibratory compaction, provision is made to achieve the desired density and reproducible results. The compaction procedure is described for both well graded granular material and single sized granular ballast material.

Results of the resilient behaviour of crushed granite show one potential application of this equipment.

2 DESCRIPTION OF THE EQUIPMENT

The equipment was adapted in 1990 for testing of full size, single sized granular material used for railway ballast in Portugal. Further development has been conducted recently to this apparatus during the Science project whereby unbound granular materials used in road construction were tested.

A schematic diagram of the apparatus is illustrated in Figure 1. This diagram shows the instrumented specimen, the loading system and the recording equipment as is described below.

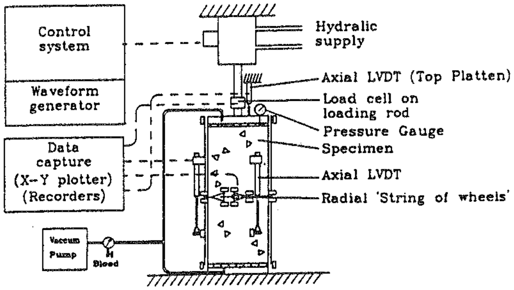

Fig.1 Hydraulic triaxial repeated loading apparatus of LNEC

2.1 Triaxial specimen

For the study of full size aggregates used in road pavements, railway ballast of other engineering applications such as earthquake problems where repeated loading occurs, the specimen size must be large enough so as not to have influence on the behaviour of the material. A general rule of thumb is that the diameter of the specimen should be not less than ten times the largest particle size, although often seven times used. Thus for road aggregates of 0/60 grading a specimen diameter of about 300mm is required. As a consequence of this and because certain equipment already existed this apparatus is able to accommodate a specimen of 300mm diameter and a height of approximately twice this.

2.2 Loading apparatus

2.2.1 Cell pressure

Due to the large specimen diameter and the low confining pressures there in no triaxial cell around the specimen as is usual with triaxial apparatus. The confining stress is simulated by applying a sub-atmospheric pressure to the inside of the triaxial specimen. An advantage of not having a pressure cell is that the transducers for measuring the strains remain accessible during the test, thus small range displacement transducers may be used.

A rubber membrane is placed inside the mould and the material compacted in layers. However because of its elastic properties this membrane applies a confining pressure on the specimen. It has been found that once the specimen is compacted the rubber membrane may be peeled off and replaced by a plastic membrane which is made up of a plastic sheet 0.3mm thick wrapped loosely around the specimen and sealed by means of plastic tape and silicone sealant. Although the membrane does not stretch it is baggy enough to allow the specimen to expand axially and laterally and does not apply a confining pressure to the specimen.

2.2.2 Axial loading apparatus

The loading frame is constructed from standard mild steel sections of sufficient strength to withstand loadings of up to 50kN. The base is made from a number of sections welded together and machined flat.

A deviator stress is applied by means of a hydraulic jack, attached to the loading frame, which applies a load to the top platen. Pressure to the jack is applied by means of a servo hydraulic control apparatus. This system can apply a maximum force of 25.7kN, which imposes a maximum deviator stress on a specimen of 300mm diameter of about 330kPa. The maximum realistic operational frequency of loading, ie. load-on load-off to load on again, of this system is about 0.5 to 0.6 Hz. The confining pressure is applied by means of a vacuum pump which can apply a maximum pressure of 70kPa.

2.3 Deformation measurements

Under repeated loading the cylindrical specimen will deform in both the axial and radial directions with each stress pulse, thus it is necessary to measure the specimen deformation in these two directions. There are two components of this deformation; one is resilient (recoverable or elastic) deformation, while the other is permanent (irrecoverable of plastic) deformation and accumulates with increasing number of loads. Essentially the permanent and resilient deformation for a single cycle in both the axial and radial directions is required, this single cycle may however be one in a series of cycles.

2.3.1 Axial deformation

The axial deformations are measured by a number of LVDTs (linear variable displacement transducers) which are glued onto the membrane at various positions. Originally the axial deformations were measured from the top platen but this has shown to give erroneous results due to end effects and measurement should be taken at either 1/3 or 1/4 of the height. Three LVDTs should be used at 120° to one another so any tilting of the specimen during loading may be identified.

Figure 2 shows an instrumented specimen and thus the axial LVDTs in position.

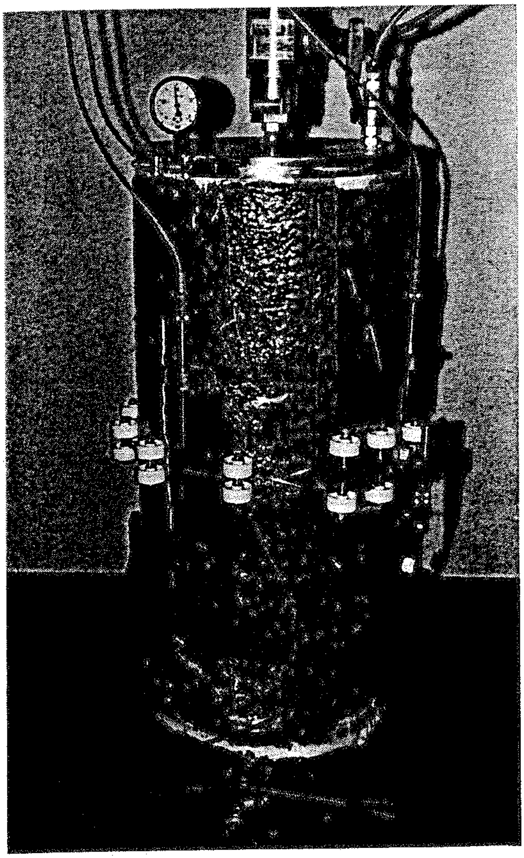

Fig.2 Triaxial cell and deformation instrumentation

2.3.2 Radial deformation

This system was based on a prototype utilised at The University of California at Berkeley, and used to test full ballast material at "Laboratório Nacional de Engenharia Civil" - LNEC.

A steel cable is threaded through ten sets of wheels and attached to an LVDT holder at each end. An LVDT then measures the increase in the circumference of the specimen and thus the radial deformation. Each set of wheels comprises of a pair of wheels on an axle through which steel cable of diameter 2mm coated in plastic is threaded. These axles are not fixed to the cable, thus the cable may move through the axles. The LDVT holders, at the cable ends, also have an axle and a set of wheels. The "String of wheels" is then wrapped around the specimen and held together by two fairly stiff elastic bands, the wheels are manually spaced around the specimen.

The radial system is shown in Figure 2 and in more detail in Figure 3.

2.4 Data capture

Data capture is conducted by means of pen plotters and pen recorders which are compatible with frequency of the repeated loading used. A load cell, between the loading jack and the top platen, sends a signal to an XY plotter, and thus the load is recorded and monitored as it is varied manually, the LVDTs all send a signal via a wheatstone bridge to pen recorders. The vacuum is controlled by means of a bleed valve and measured by two pressure gauges one at the pump and the other through the top platen. This method of load control and data capture although functional is very time consuming and prone to operator errors, work is at present being conducted to change the system to a more automated system.

3 TEST PROCEDURE

3.1 Specimen preparation and compaction

The material is compacted in a split mould which has three sections. The internal diameter of the mould is 310mm thus allowing for the membrane which is placed inside the mould.

The bottom platen has a drainage hole in the side. Both platens have groves cut in the top coinciding with the holes drilled in a porous plate placed between the specimen platen to allow the free entry and distribution of the vacuum. The top platen has a drainage hole through the top of the platen and provision for a pressure gauge has been made on the opposite side of the platen. The bottom plate fits on a base plate which has four threaded holes at certain positions around the specimen to which four vertical bars may be bolted and attached to one another in pairs for fixing measuring equipment securely.

To achieve similar densities attained during road construction, ie. optimum density less 2% as defined by using the modified Proctor test, a vibrating hammer of weight 300 to 400N and vibration rate of 750Hz with a base diameter of 145 mm is used to compact the specimen. Due to the base area being less than the area of the specimen shear is induced in the specimen and greater densities are obtained than using a full faced, 300mm diameter, base plate vibrator.

About 100kg of the material is prepared at the correct moisture content, covered and left overnight. A rubber membrane, 2mm thick, is

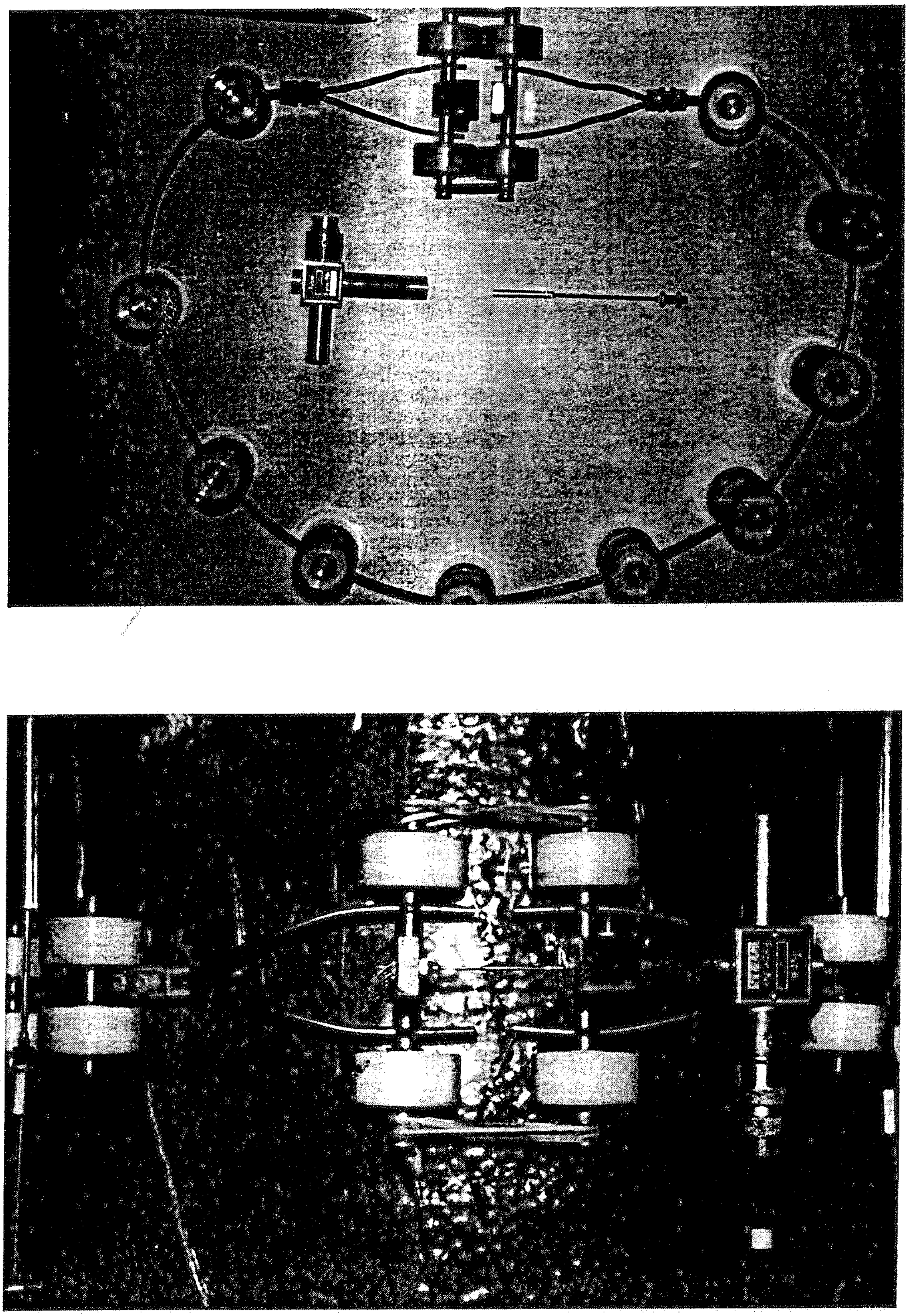

Fig.3 Radial deformation system

stretched over the first of three different sections of the mould. Exact, 10kg, quantities of the material are weighed and placed in the mould, these are levelled by hand and compacted with the vibrating hammer. Since accurate compaction is required the layer thickness is monitored carefully to yield the correct density. The surface of each compacted layer is roughened, by scratching, to improve the interlock between the layers. As the first mould section fills the second and the third sections are added.

After ten layers are compacted to the correct height, thus density, the top platen is placed on the specimen. A disc of unwoven geotextile (100 g/m2) compressed and coated with a water-resistant silicone emulsion aerosol placed between the specimen and the porous plate has proven effective for stopping the loss of moisture but allowing the free passage of air to and from the specimen. The specimen is then left with the drainage inlets open to the atmosphere for three days to allow for moisture equilibrium and strain stabilisation.

The homogeneity of the density is checked by a gamma ray auscultation method, conducted at 50mm intervals down the specimen. A typical result of this density test on a specimen is shown in Figure 4.

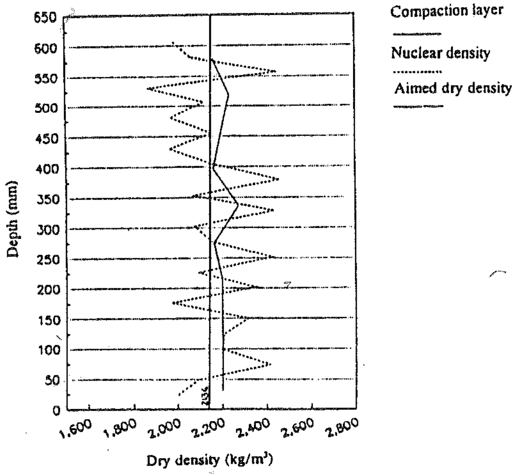

Fig.4 Specimen density obtained by gamma-ray auscultation

The evaluation of the density of well graded materials is easily obtained because the specimens have a well defined geometric form, the finer particles fill the gaps between the larger particles. However, for single sized graded materials the surface of the specimen is very irregular, and consequently it is necessary to evaluate the true volume, thus density, of the specimen. Yoo at al. (1978) analysed the error obtained by the consideration of plane and irregular surfaces.

Nunes and Gomes Correia (1991b) tested a single sized ballast material measured the volume of voids between the actual surface of the specimen and the regular shaped assumed surface, the vertical surface of the mould and the top and bottom platens. They found that the volume between the top platen and the specimen differed for the vertical and bottom surfaces. They conclude that the correction factor as proposed by Yoo et al. (1978) is not sufficient and may cause an overestimation of the density, and to conduct an accurate evaluation of the true volume of single sized materials the volume of the voids must be determined for all the external surfaces.

3.2 Resilient characteristics of a crushed granite

For the development of more effective road pavement design methods a rational study of the mechanical behaviour of the constituent materials and appropriate analysis to match the actual pavement behaviour is necessary. During the Science project a number of different unbound granular materials were tested using this apparatus, one of the materials and the results of a test programme on that material is presented here.

3.2.1 Material description

The material tested is a crushed granite called Microgranite from France. This material is used in unbound granular layers in road construction, generally in the subbase layers but sometimes in the base layers where thick asphalt layers are used. The grading curve for this material is shown in Figure 5. The material was compacted as described above to a dry density of $\rho_d = 2136 \text{kg/m}^3$ at a moisture content of 3.3%, these values correspond to the dry density and moisture content at optimum moisture content less 2% as defined using the modified Proctor test.

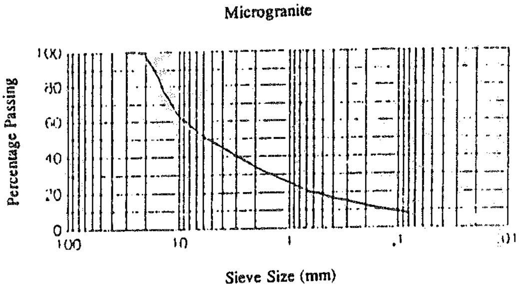

Fig.5 Grading curve of microgranite

3.2.2 Definition of the parameters

The results are analysed in terms of total stresses where the following stress parameters are used:

$$p = \frac{1}{3}(\sigma_1 + 2\sigma_3) \qquad (1)$$

where p = mean normal stress; σ_1 = major principle stress; and σ_3 = minor principle stress.

$$q = \sigma_1 - \sigma_3 \qquad (2)$$

where q = deviator stress.

$$\theta = \sigma_1 + 2\sigma_3 = 3p \qquad (3)$$

where θ = first stress invariant.

For repeated axial loading with constant confining pressure as with this apparatus the resilient modulus and the Poisson's ratio are defined as:

$$M_r = \frac{\sigma_{1r}}{\varepsilon_{1r}} \qquad (4)$$

where M_r = resilient modulus; σ_{1r} = repeated major principal stress; and ϵ_{1r} = repeated strain in the direction of the major principal stress.

$$\nu_r = -\frac{\varepsilon_{3r}}{\varepsilon_{1r}} \qquad (5)$$

where ν_r = resilient Poisson's ratio; and ϵ_{3r} = repeated strain in the direction of the minor principal stress.

3.2.3 Repeated triaxial testing and analysis of the results

The repeated load test programme followed a test procedure as stipulated by the Science project, thus a number of different stress paths were applied to the specimen. One hundred load pulses were applied to the specimen, stresses and strains were recorded during the last ten cycles ant the values of the one hundredth cycle recorded providing little difference between this and the other nine cycles was found.

Table 1 shows the stress and strains for twelve stress paths applied to this specimen. For each stress path the first stress invariant is calculated. The results are filted to the well known Kθ model and the resilient modulus may be plotted against the observed resilient modulus and, as shown in Figure 6, a fair prediction of the resilient modulus was obtained.

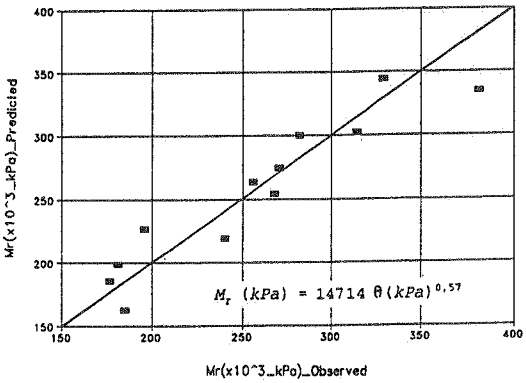

Fig.6 Adjustement of M_r-θ Model

Table 1. Resilient test results.

Confining stress σ_3 (kPa)	Repeated deviator stress q (kPa)	Resilient axial deformation ϵ_{1r}	Resilient radial deformation ϵ_{3r}	First stress invariant θ (kPa)	Resilient moduli M_r (MPa)
17.9	14.5	78	0	68.2	184.8
17.9	32.6	185	-32	86.3	176.8
17.9	43.5	240	-47	97.2	181.1
17.9	68.9	352	-77	122.6	195.8
30.6	23.6	98	0	115.4	240.0
30.6	58.0	216	-38	149.9	268.1
30.6	79.8	295	-62	171.6	270.5
30.6	108.8	386	-86	200.6	281.9
44.7	25.4	99	0	160.0	255.8
44.7	68.9	219	-32	203.1	314.3
44.7	108.8	285	-52	243.0	381.3
44.7	121.5	369	-67	255.7	328.9

Thus by the Kθ model, defined as:

$$M_r = K_1 . \theta^{K_2} \qquad (6)$$

where $K_1 = 14714$ and $K_2 = 0{,}57$ for Microgranite.

CONCLUSIONS

The equipment presented is appropriate to study the resilient behaviour of granular materials, mainly those with particle sizes until 63mm.

The deformation instrumentation used give very accurated results.

The apparatus apply a constant confining pressure, wich is suitable to modelling resilient behaviour of granular materials by the M_r-θ model. However, this is a limitation to use more advanced models.

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