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

Summary

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1 INTRODUCTION

The purpose of this session is to present research results whose primary concern is with the behaviour of subgrade soils under repeated loading in the context of the role they play in pavement design.

The six papers assigned to this session contained three papers from the Science project and three from outside the Science project.

The objective of the Science papers deal with:
- Harmonization of a test procedure for triaxial testing of subgrade soils.
- Prediction of subgrade moisture conditions for purposes of pavement design.
- Resilient behaviour of soils.

The three other papers, outside the Science programme, presented:
- A study on the influence of the behaviour of a clay subgrade on the performance of a flexible pavement. (First paper - Nottingham University).
- A study on the cyclic behaviour of l'Ennerie sand, a material used as subgrade soil at the full-scale, pavement test facility of the Laboratoire Central des Ponts et Chaussées, in Nantes. (Second paper - LCPC, LRCP Saint-Brieuc).
- A study on the cyclic behaviour of in situ samples of various fine-grained subgrade soils. (Third paper - Swedish Road and Transport Research Institute).

2 FINDINGS OF SCIENCE PROJECT

2.1 Harmonization of a test procedure for triaxial testing of subgrade soils

In this theme, there are three main aspects to be considered:

a) Equipment

All the 4 laboratories of the Science project use the triaxial cell. In LNEC, UNOT and LRPC of Clermont-Ferrand, the equipment uses a servo-hydraulic system to cycle both axial load and confining pressure. In DUT, only axial load can be cycled by a servo-hydraulic system; the confining pressure being constant and applied by a pneumatic system.

b) Instrumentation and data capture

Traditionally, triaxial samples were assumed to deform uniformly so that measurements of pore pressure at the end of the specimen, overall axial strain measurements and deduction of radial strains from overall axial strain and volume change could be assumed to give representative values. However, with the recognisation that uniformity is less inevitable than had been supposed, attempts were made in instrumentation devices to measure pore pressures at middle-height, to measure axial and radial strains over a central gauge length that is remote from the ends of the specimen. This development of instrumentation has been necessary to discover the true behaviour of soils at very low strains which can be easily masked by apparatus deficiencies. Also the axial load measurement inside the triaxial cell is important to avoid the friction by the piston crossing the top of the triaxial cell.

The three laboratories involved in the Science project: LNEC, UNOT and LRPC use all these new developments in instrumentation, only DUT uses the axial strain measurements outside the triaxial cell because it uses a specimen with greater dimensions.

All the laboratories have in their equipment pore pressure measurement facilities, except UNOT for the case of negative pore pressures.

All the apparatus use a computer data acquisition system, but only UNOT and LRPC have facilities for computer controlled axial load and confining pressure.

c) Recommendations for test procedures

The objective of this sub theme is to define the test procedures for characterizing the resilient and permanent behaviour of subgrade soils under repeated loading.

In order to study the repeatability of the different equipments on the soil behaviour, a first test programme was carried out, using two types of soils: Fontainebleau sand and London clay. This test programme was performed according to the experience of each laboratory, and following a test procedure specifying the stress paths. This first experience was unsuccessful, and in consequence conducted to a more fundamental work consisting in verifying the accuracy of the instrumentation used by each laboratory and study the repeatability of the different equipments using an artificial specimen with known mechanical properties.

After this fundamental work, a second test programme was established, using only one soil and a very accurate test procedure.

From these original repeatability tests performed in the Science project, it appeared that repeated load triaxial tests on subgrade soils are affected by serious scatter, due to several factors, such as:

- The small strains measured in the tests. The elastic strains are generally of the order of 10^{-4} to 10^{-3}, which represents displacements of about 10 to 100 microns (for the dimensions of specimens used).
- The large variations of soil stiffness with suction (especially in the case of fine-grained soils).
- The influence of the method of compaction of the specimens on the permanent strains of the soil.

Taking into account the results obtained previously, the experience of the different laboratories and the important factors affecting the mechanical behaviour of subgrade soils, a test procedure was recommended to study the resilient behaviour and permanent deformations of subgrade soils under repeated load triaxial testing. These recommendations stressed the necessity of:

- Measuring strains locally, in the central part of the specimen, to avoid errors due to bedding and end restraint.
- Measuring systematically the suction of the specimens.
- Using reliable compaction methods, producing homogeneous specimens.

2.2 Prediction of subgrade moisture conditions for purposes of pavement design

The paper on moisture conditions presents a review of studies of moisture contents in subgrade soils carried out in various countries, and draws some conclusions concerning the choice of design moisture contents for pavement design. In particular, it shows that in temperate climates, the maximum field moisture contents in subgrade soils can be estimated by the relationship $w_{MAX} = Fw_{OPM}$, where F is a factor of safety ensuring that there is only a small probability of exceeding the maximum moisture content. The values proposed for F are 1.34 for a probability of 90% and 1.46 for a probability of 95%. This paper also presents an approach for estimating soil suction using plasticity index and water table level. Typical relationships between suction and water content, for soils of different plasticity index, are also presented.

2.3 Resilient behaviour of soils

The experimental results obtained during the Science project indicated that:

- The behaviour of cohesionless soils (sands) is very similar to that of unbound granular materials. This type of behaviour is relatively well represented by the non-linear elastic model proposed by Boyce, expressed by:

$$\epsilon_v = (\frac{1}{K_1})\, p^n\, (1 - \beta \frac{q^2}{p^2}) \qquad (1)$$

and

$$\epsilon_q = (\frac{1}{3G_1})\, p^{n-1}\, q \qquad (2)$$

where: $p = (\sigma_1 + \sigma_3)/3$, $q = (\sigma_1 - \sigma_3)$, $\epsilon_v = (\epsilon_1 + 2\epsilon_3)/3$, $\epsilon_q = 2/3(\epsilon_1 - \epsilon_3)$, $\beta = (1-n)K_1/6G_1$; K_1, G_1, n are the three parameters of the model.

- Fine-grained soils (clays) present a different behaviour, governed mainly by the value of the suction, and of the cyclic deviator stress (the stiffness of the soil decreases as the deviator stress increases). The relationship adopted in the Science project to describe this behaviour is:

$$M_r = C + A\, p_0 - B\, q_r \qquad (3)$$

where: M_r is the resilient modulus, p'_0 the mean effective stress or suction at zero confining stress and q_r the cyclic deviator stress. A, B and C are the three parameters of the model.

- The silt studied in the Science project presented an "intermediate" behaviour, similar to that of unbound granular materials at low water contents (almost linear elastic), and similar to that of fine-grained soils at high water contents (decrease of stiffness with increasing deviator stress).

3 CONTRIBUTIONS OF EXTERNAL PAPERS

The papers outside the Science project tend to confirm some of the results obtained in the project.

The study on l'Ennerie sand shows that the behaviour of this soil is very similar to that of unbound granular materials, and proposes to describe this behaviour using the Boyce model. Moreover, it appears that the behaviour of this sand becomes increasingly non-linear as the water contents increases. The study also shows that the stiffness of the sand varies largely with the degree of saturation S_r, and proposes relationships between S_r and the parameters of the Boyce model.

The paper of the Swedish Road and Transport Research Institute presents results of triaxial tests performed on in situ samples of clays and silts. The behaviour of the clays is strongly non-linear, with a stiffness decreasing as the level of deviator stress increases. the following relationship is proposed to describe this behaviour:

$$M_r = A - B\, q_r \qquad (4)$$

where: M_r is the resilient modulus, q_r the cyclic deviator stress, and A and B the parameters of the model.

The behaviour of the silts, however, is almost linear elastic for the stress levels applied in the tests. Another interesting result of the study is the lack of relationship between resilient and permanent strains measured in cyclic triaxial tests. For example, in the case of the silts, the permanent strains seem to depend strongly on the water content ant the uniformity coefficient of the soil, but not the resilient strains.

4 CONCLUSIONS

This session of the Euroflex Symposium on soil subgrades gives a good overview of the research carried out in several european countries on the behaviour of subgrade soils. From the different contributions presented to this session, it can be concluded that:

- The study of the cyclic behaviour of subgrade soils requires sophisticated test equipment, and good experience: cyclic tests on subgrade soils are performed at low stress levels, and include large numbers of load cycles (10^5 or more). Moreover, the soils must be tested in unsaturated conditions, with a measurement of the suction during the tests.
- The models used in practice to describe the behaviour of subgrade soils remain very simple (linear or non-linear elastic models, expressed in terms of total stresses), for several reasons: the behaviour of partially saturated, fine-grained soils is complex and difficult to analyze in terms of effective stresses; test results are affected by serious scatter, which makes accurate modelling of the behaviour difficult; complex models require detailed laboratory studies, which are too expensive and too time-consuming for routine applications.
- It is necessary to distinguish at least two types of subgrade soils: cohesionless soils, and fine grained, cohesive soils. The stiffness of cohesionless soils depends mainly on the mean stress p (the stiffness increases with increasing p). The stiffness of fine-grained soils depends mainly on the negative pore-pressure existing in the specimen (suction), and on the value of the cyclic deviator stress q_r (the stiffness decreases with increasing q_r).
- The stiffness of unsaturated fine-grained soils is largely dependent on suction. For this reason, to take into account accurately the behaviour of a subgrade soil in the design of a pavement, it is necessary to know the moisture conditions (or suction) of the soil. For this reason, it may also be interesting to develop a two-stage pavement design approach, taking into account successively: the moisture conditions during the construction of the pavement; the long term, equilibrium, moisture conditions.
- There is a need for more parametric studies, to determine clearly the influence of the behaviour of the soil on the design parameters of different types of pavements.