The effects of stress and pore water pressure states on the resilient properties of granular materials

Les effets des états de contrainte et de pression interstitielle sur les propriétés résilientes des matériaux granuleux

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SYNOPSIS: This study concerns the evaluation of the resilient properties of granular materials as used in design and structural evaluation of flexible pavements. Based on the results of cyclic triaxial test program performed on a sand, clayey sand and a aggregate it is shown that the Kθ model does not properly describe the response of granular materials under a wide range of stress paths. For such conditions a more detailed stress-strain model was used and found to be applicable for saturated and unsaturated conditions using the effective stress principle. For more complicated stress situations applied with a hollow cylinder apparatus, which is intend to simulate the type of stress that occurs in roads under a moving wheel, a more general law is necessary.

1 INTRODUCTION

The soils beneath pavements and the unbound aggregate layers of road construction are subjected to a variety of stresses and pore water pressures. The levels of these stresses and pressures are very different from the conditions usually considered in geotechnical engineering problems.

The conditions peculiar to soils and aggregates in or under pavements are as follows:

a) normal stresses in unloaded pavements are very low;

b) pore pressures are small in magnitude and frequently negative;

c) the materials are often partially saturated;

d) traffic loading applies repeatedly rotated stress field to the soil or aggregate.

In order to be able to design and analyse pavements structures (both concrete and bituminous) it is necessary to quantify the stiffness properties of the lower layers of the construction. Many models have been proposed for this (some of which are covered in this paper) but, because of the complexities outlined above, they have generally been developed for simplified cases.

It is the purpose of this paper to compare some existing models for granular materials behaviour with laboratory test results obtained on samples under controlled, realistic, stress and pore water conditions.

Many of the findings will also be applicable to other soils but discussion of this is beyond the scope of this paper.

The paper commences with a brief summary of the test methods used.

Then the comparison of model prediction and measured behaviour is considered under three headings.

Firstly the effect of stress level is reviewed. Secondly the arrangement of stresses, and particularly the effect of imposed stress rotation, is discussed. Finally the role of pore pressures, especially in partially saturated soils is considered.

2 TEST METHODS

The primary device used in the testing work has been the repeated load triaxial test apparatus. Machines capable of testing samples of 70 mm and 150 mm diameter, have been used at , LRPC-Clermont Ferrand, LNEC - Lisbon and at the University of Nottingham. Each piece of equipment is servo-hydraulically controlled and features full on-sample instrumentation and the ability to cycle both deviatoric and confining pressures.

Further details on the equipment can be found in Gomes Correia (1985,1987) and Thom (1988), respectively.

Some modifications to the basic machines have been carried out in order to facilitate suction measurements and these are described in a following section.

In addition to the triaxial test equipment a repeated load hollow cylinder test apparatus (HCA) was developed (O'Reilly et al. 1987) to investigate the effect of a repeatedly imposed rotating stress field. The HCA as used was only able to test dry material of maximum size 4 mm to which a constant confining stress was applied by a vacuum. A repeated axial stress and an independent repeated torque could be applied, thus simulating a succession of wheel loads approaching, crossing and departing from an element of sand contained in the wall of the cylindrical sample.

3 EFFECT OF STRESS PATH

In common with most geotechnical materials, stiffness response is highly stress-dependent. The conventional manner of dealing with this is the " Kθ " model (Hicks & Monsmith 1971) for which:

$$E = K_1 \theta^{K_2}$$

where E is the elastic modulus, θ is the bulk stress (the sum of any three orthogonal normal

stresses) and K_1 and K_2 are material constants.
This model has been applied to a sand (fig 1) which was tested in the triaxial apparatus (Gomes Correia 1985) over a wide variety of stress paths in the compression zone (fig.2). Whereas the Kθ model may reasonably predict response to axial stresses, when repeated confining stresses are applied the prediction of strains may not be very good, and this is reflected in Figure 3. The observed volumetric strain during a wide variety of stress paths is compared with the predicted value calculated on the bases of the generalized Hooke Laws, assuming a constant Poisson's ratio of 0.35 (a conventional value for a granular material).

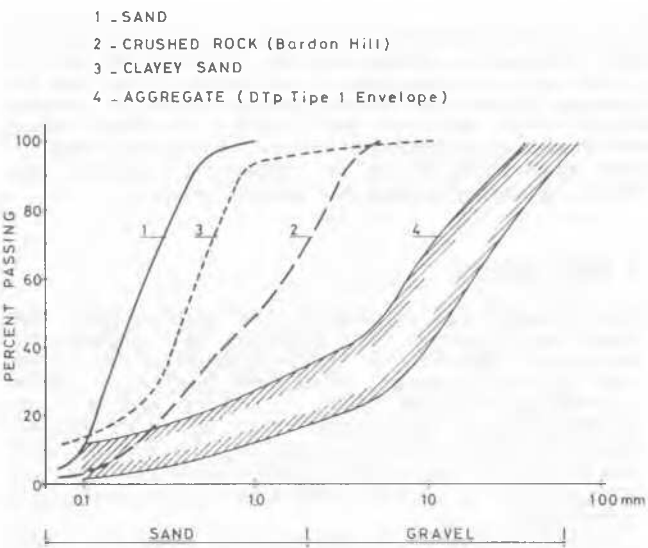

Fig 1. Gradings of materials tested.

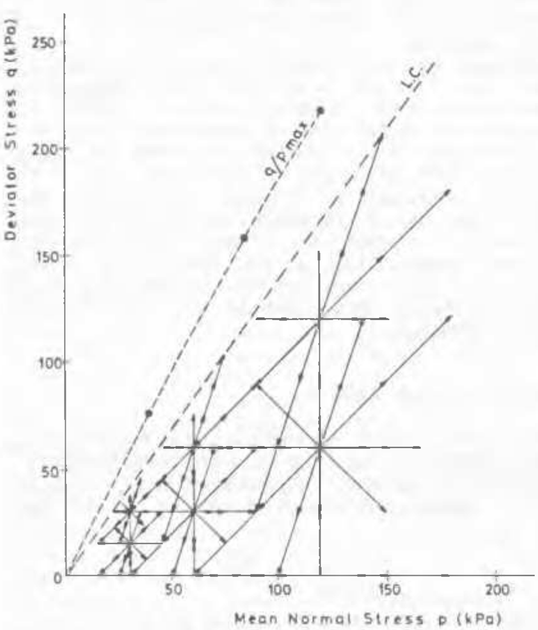

Fig 2. Stress paths used in sand test.

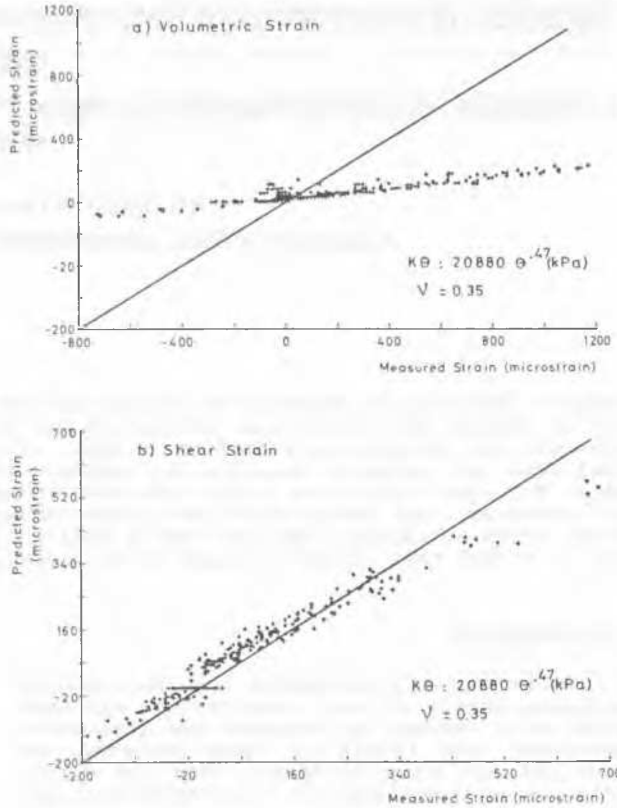

Fig 3. Prediction of volumetric and shear strains - Kθ model.

Clearly the model is inadequate. It was for this reason that an improved model was developed by Pappin (1979). He separated volumetric and shear strain effects, producing a different model for each, but both of the general form:

$$\epsilon = \text{fn}\ \delta(q,\ p')$$

where ϵ is either volumetric or shear strain, q is the deviatoric stress and p' the mean normal effective stress. δ indicates that ϵ is a function of the change in the parameters q, p'. Full details of the two functions are contained in Pappin (1979).

Pappin's equations were used to predict the volumetric strain behaviour of the sand, as before. Figure 4 shows that the prediction is now very good and thus the Pappin model is prefered to the Kθ model. This is a useful finding as the original model was developed for aggregates.

When shear strains are considered the Kθ model is fairly reliable although the Pappin model is even better.

4 EFFECT OF APPLIED STRESS SYSTEM

In the triaxial test the imposed stresses must necessarily be principal stresses. In normal equipment the axial stress will always be the major principal stress and the confining pressure will provide the minor principal stress. Clearly this does not simulate the stresses experienced by geotechnical materials in roads, even though cycling of radial and axial stresses (in, and in opposite phase) may be used. In pavements, stress levels not only increase as traffic passes, but also the plane on which the principal stress acts remains approximately orthogonal to a line joining the wheel and the soil element. Thus the stress field rotates as the load passes.

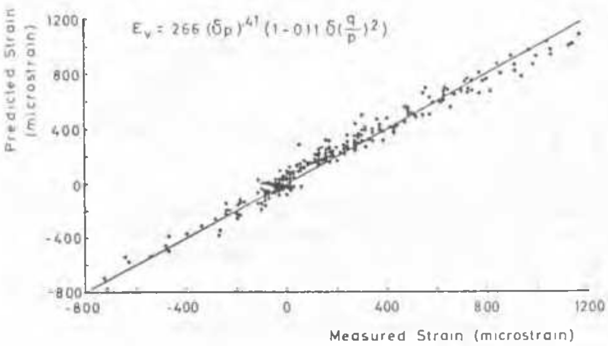

Fig 4. Prediction of volumetric strain - Pappin model.

In order to determine whether or not this rotation effect was important HCA testing was carried out on a sand derived from a crushed rock (Fig. 1).

Firstly, only repeated axial loading was applied. Figure 5 shows that the Pappin model adequately predicts the volumetric strain under these limited conditions in the HCA. Next the test was repeated but this time with the addition of a repeated torque. The prediction based on the Pappin model is now rather poor (see Figure 6) particularly at low stress levels. If the Pappin model is used to predict shear strains the results are even worse with a near random variation of predicted to actual values. A new model is therefore being developed to incorporate the effects of imposed shear. The same data as that presented in Figure 6 is presented in Figure 7, this time with the predicted value being derived from the new model. The model is rather complex and can not be discussed here. Interested readers should consult Thom (1988).

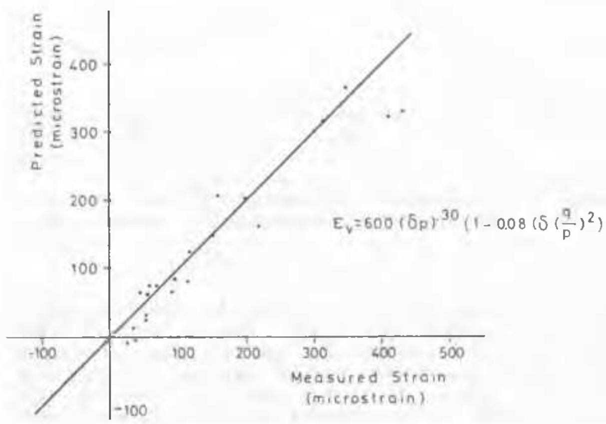

Fig 5. Prediction of volumetric strain - Pappin model (data from HCA under repeated axial loading).

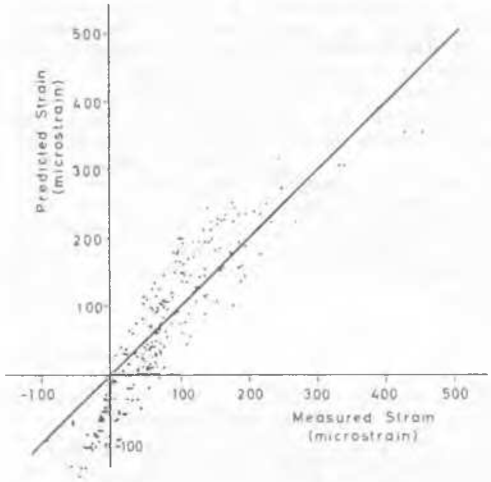

Fig 6. Prediction of volumetric strain - Pappin model (data from HCA under repeated torque).

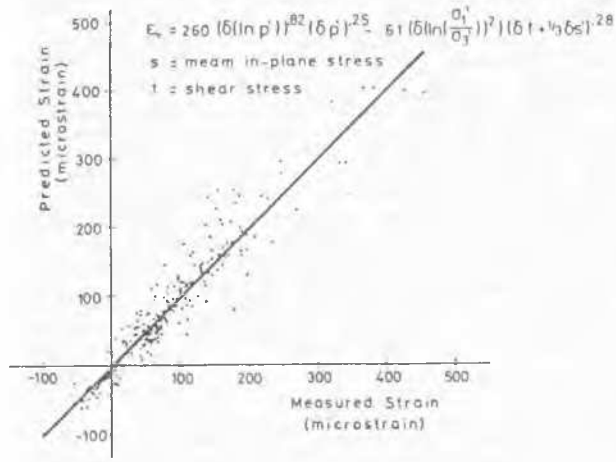

Fig 7. Prediction of volumetric strain - Thom model (data from HCA).

5 EFFECT OF PORE WATER PRESSURES

The models discussed so few were developed for dry soils. As real pavement materials are not dry it is important to determine whether granular soils obey the effective stress principle under cyclic loading. Pappin (1979) showed that a saturated granular material could be described by his models if an effective stress approach was adopted. Gomes Correia (1985), has show that the Pappin model can also be used in effective stress terms to describe both the volumetric and shear resilient behaviour of a saturated sand.

For the clayey sand (Fig. 1) it would not be sensible or practicable to develop a model for the dry condition, since such a soil cannot exist. However, models developed on other dry soils have been calibrated against its behaviour, assuming the effective stress principle applies. Reasonable results, were obtained (Gomes Correia 1985). The volumetric strain relationship is shown in Figure 8.

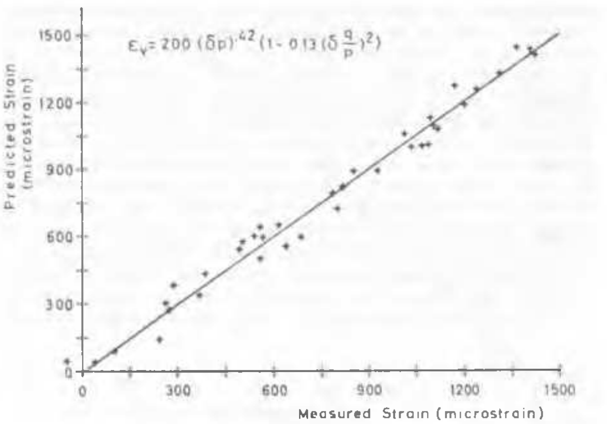

Fig 8. Prediction of volumetric strain using effective stress principle in a saturated clayey sand.

However in most pavements partially saturated materials exist. This may be because of incomplete drainage control (Dawson 1985) or because of the fine grading of the soil. As a result, it is almost certain that pore suctions will exist. Pavement performance will often be very sensitive to the level of such suctions (Brown and Dawson 1985). Suctions have been measured on a number of occasions both in the laboratory (OCDE 1973), (Dawson 1985) and in the field (Van Ganse and Brull 1971), (Raimbault 1986).Thom (1988) carried out uniaxial tests on a dolomite limestone aggregate. He demonstrated that the partially saturated aggregate can, at certain moisture contents, compaction level and grading, exhibit a small strength. If this-strength is compared with that of a similar, dry, sample the effect of suction can be deduced (fig. 9), (Thom 1988). In all cases the suctions measured have been quite small (usually 4 - 8 kPa) and it may therefore be argued that they can be ignored and a total stress approach adopted. This was done for a partially saturated sand using the Pappin model and the result is shown in Figure 10 (Gomes-Correia 1985).

Because of this poor prediction some developments of the triaxial apparatus for measuring negative pore pressure were carried out so as to study partially saturated soils.

The negative pore pressures levels applied in the soil tested use the suction plate method. At the bottom of the specimen a porous ceramic ring with an air entry value of 100 kPa was used. At the centre of this ring was placed a small diameter, membrane (permeable to air but not to water) in order to control the pore air pressure.

The negative pore water equilibrium is established with water provided by a self compensating water, or mercury control system, applied at a known suction beneath the porous ring. The system can be adapted to apply higher suctions levels by changing the porous discs for high air entry values, and using the pressure plate method. This is a variant of the suction plate method in which an air pressure is applied by the special membrane while the water in the porous ring remains at atmospheric pressure. The results of Figure 10 are represented in Figure 11 using an effective stress approach and incorporating the measured suctions. It can be seen that the use of a total stress approach, ignoring suctions, is significantly worse. Similar improved modelling of shear strains can also be achieved by the effective stress with suction approach.

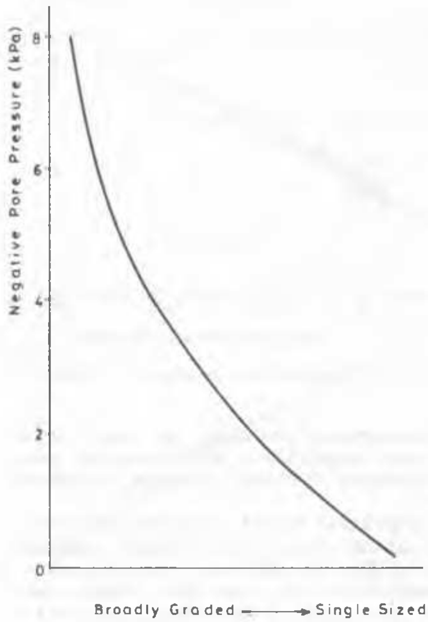

Fig 9. Deduced negative pore pressures due to suction.

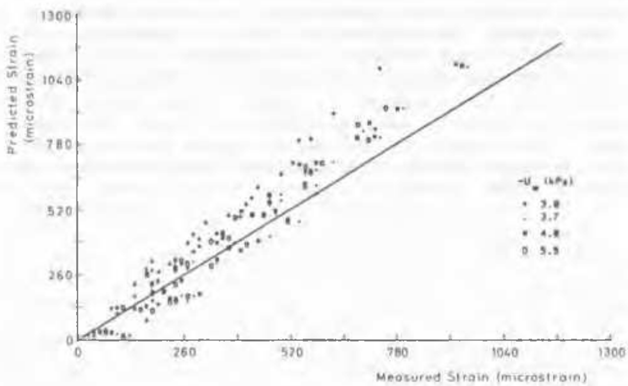

Fig 10. Prediction of volumetric strain using total stress in a partially saturated sand.

Similar findings were found by Thom (1988), who tested aggregate (Fig. 1) at varying degrees of saturation. He tested the material with pore pressure coefficient, B, values (Skempton 1954) Of 0,0.5 and 0.9. Using his model (which for triaxial testing gives comparable results to that of Pappin (1979) - see above) he obtained a good prediction of both volumetric and shear strain (Fig. 12).

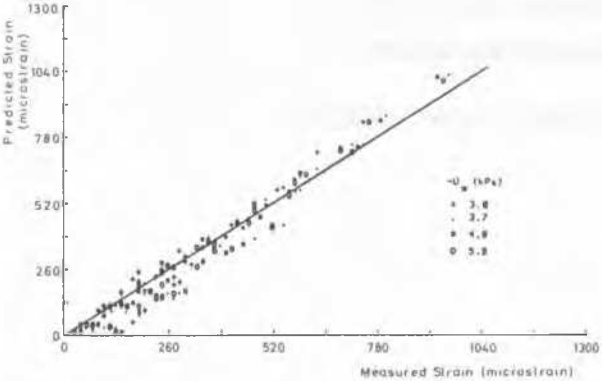

Fig 11. Prediction of volumetric strain using effective stress in a partially saturated sand.

$$\varepsilon_v = 410\,(\delta(\ln p'))^{.82}(\delta p')^{1} - 162\,(\delta(\ln(\frac{\sigma_1'}{\sigma_3'}))^2)^{1.52}$$

$$\varepsilon_s = 50\,(\delta(\ln(\frac{\sigma_1'}{\sigma_3'})))^{.86}\,(\delta t + {}^1\!/_3\,\delta s')^{.47}$$

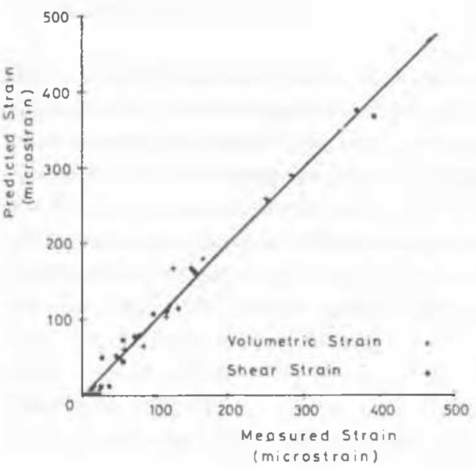

Fig 12. Prediction of volumetric and shear strains using effective stress in a partially saturated crushed granite.

6 CONCLUSIONS

1. When aggregate, sands and clayey sand were tested under repeated loading, their resilient strain response was highly dependent. This is particularly so far volumetric strains.

2. The Kθ model is not adequate for predicting strains, particulary volumetric strains, under such stress conditions. For triaxial loading the Pappin model was far superior.

3. Real pavement materials, particularly those high in the structure, are subjected to repeated stress rotation under wheel loading. The Pappin model cannot adequately predict strains under these conditions, particularly the shear strains. Thom's model appears a good approach for overcoming this problem.

4. Repeated hollow cylinder testing is one way of studying the influence of rotating principle stress fields.

5. An effective stress approach, that is incorporating a measurement of pore water pressures, is required to study the resilient properties of granular materials.

6. In unsaturated granular materials negative pore pressures usually occur and must be measured. A technique has been described for a measuring and controlling negative pressures in the triaxial test.

7. The response of partially saturated granular materials to repeated loading requires an effective stress model incorporating measurements of those pore pressures. These pressure must be incorporated even though they may be small.

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