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Stress-strain behaviour of compacted geomaterials for pavements

Comportement contrainte-déformation de geomatériaux pour chaussées

A. Gomes Correia
University of Minho, Portugal

L. Q. Anh Dan, J.Koseki & F. Tatsuoka
University of Tokyo, Japan

ABSTRACT
This paper presents some new and significant aspects of pre-failure deformation characteristics, particularly stress-strain properties at small strains, of crushed unbound granular materials used in pavement construction. The data was obtained from a series of precision cyclic triaxial tests performed at the Institute of Industrial Science, University of Tokyo, using stress paths and strain levels representatives of pavement field conditions. Based in this data, effects of stress state and strain level in Young's modulus are discussed to some depth.

RÉSUMÉ
Cet article présente des aspects nouveaux et significatifs des caractéristiques des geomatériaux, en particulier les propriétés contrainte-déformation en petites déformations des matériaux granulaires concassés non traités utilisés dans la construction routière. Les donnés ont été obtenus par des essais triaxiaux cycliques de précision réalisés à l' "Institute of Industrial Science, University of Tokyo", en utilisant des chemins de contrainte et des niveaux de déformation représentatives dans les chaussées. Ces données ont permis de mettre en évidence les effets de l'état de contrainte et du niveau de déformation dans le Module d'Young.

1 INTRODUCTION

Accurate evaluation of the stress-strain property for a strain amplitude of about 0.001% to 0.1% of soils, including unbound granular materials (aggregates) that are often used in the pavement engineering, is essential for modelling the material behaviour (Gomes Correia & Biarez, 1999; Gomes Correia et al., 2001). Such modelling is important for rational pavement design in particular. As this property strongly depends on not only the stress state but also the strain level even at these small strains, it should be carefully evaluated by accurately measuring stresses and strains along stress paths representative of typical field conditions.

In this paper, part of the results from experimental study using two types of crushed unbound granular materials along different isotropic and anisotropic stress paths. Effects of stress state on the very small strain Young's modulus are discussed, as well as the stress-strain behaviour during a large number of cycles. It is demonstrated in particular that the very small strain Young's modulus become more anisotropic as the stress state becomes more anisotropic. It is also shown that, by that property, after the deformation property has significantly reversible cyclic pre-straining, the tangent Young's modulus increases significantly, therefore the secant one also increases, with an increase in the deviator stress (i.e., with an increase in the axial strain) until the axial strain becomes a certain value in triaxial compression at constant confining pressure.

2 TRIAXIAL TESTING

2.1 *Testing materials*

Two types of granular materials having the grain size distributions shown in Figure 1 were used. Some physical properties of these two materials are listed in Table 1.

The first material is an aggregate of granite actually having a maximum grain size of 31.5 mm, which is used to construct road base layers. The second one is a scaled material of the original one described above, having a maximum size of 12.5 mm and the same percentage of grains less than 0.075 mm as the original one (Fig. 1). These two materials are relevant to the use for granular layers of pavement and railways structures.

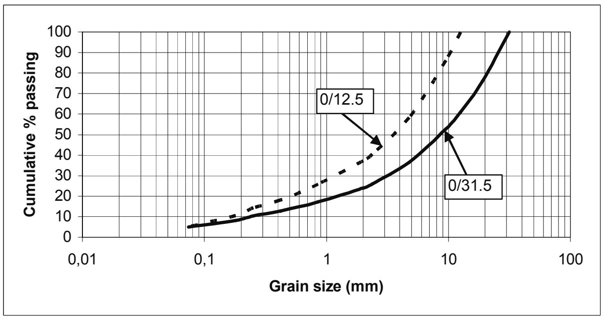

Figure 1. Grain size distribution curves of investigated unbound granular materials

Table 1. Physical properties of investigated unbound granular materials

Material	D_{50} (mm)	U_c	Modified Proctor		G_s
			w (%)	ρ_d (Mg/m^3)	
0/31.5	8.5	53	5.9	2.310	2.71
0/12.5	3.5	28	6.2	2.125	2.71

Material	Compaction conditions		
	w_0 (%)	ρ_{d0} (Mg/m^3)	e_0
0/31.5	3.9	2.193	0.236
0/12.5	4.1	2.216	0.223

2.2 *Triaxial apparatus*

A relatively large triaxial apparatus (Figure 2) was used with a square prismatic specimen (58 cm high and 23 cm times 23 cm in cross-section). Both axial and lateral strains were locally and sensively measured with a set (in total ten) of local deformation transducers (LDTs; Goto et al. 1991). The loading system, which consisted of a hydraulic system for the axial load and a pneumatic system for the lateral pressure, was able to apply various stress paths. The testing method described above has been used successfully for sands (Hoque et al. 1996) and for gravels (Jiang et al. 1997).

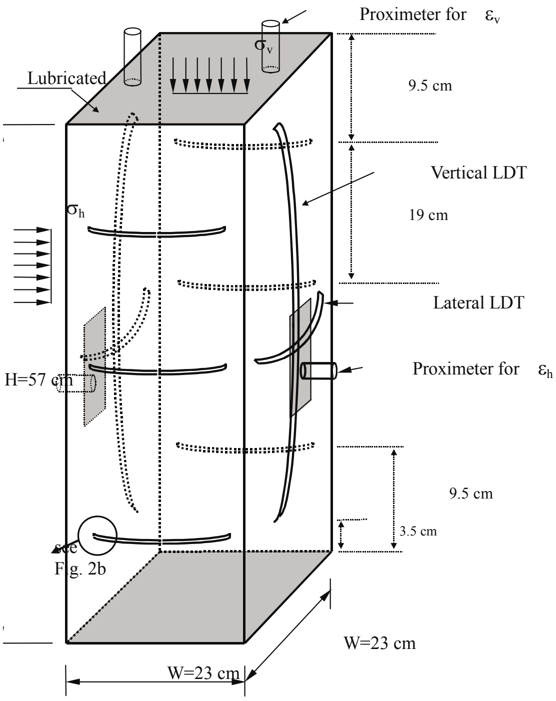

Figure 2. Triaxial apparatus (Hoque et al. 1996)

2.3 *Testing programme*

The specimens were compacted to a very dense state, representative of road base granular layers (Table 1). The compaction technique is describedin Gomes Correia et al. (2001). After assembling all the triaxial system, the specimen was isotropically compressed to a cell pressure of 40 kPa. Then, a series of isotropic triaxial compression stress paths (fig. 3) and isotropic and anisotropic stress paths at different ratios $R = \Delta\sigma_v/\Delta\sigma_h$ (fig. 4), were applied. At a number of different stress states along these stress paths, unload/reload cycles with a very small vertical stress increment were applied.

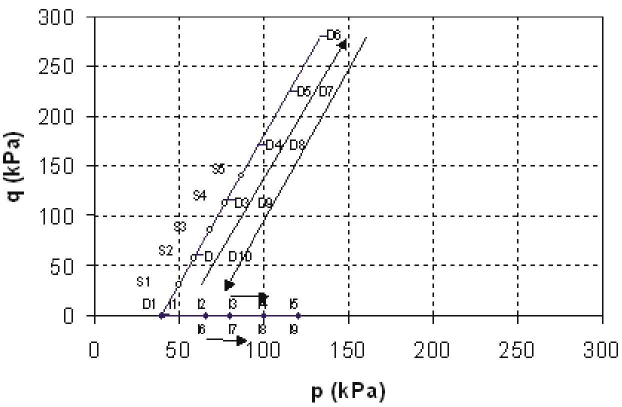

Figure 3. Isotropic and triaxial compression stress paths (Gomes Correia et al. 2001)

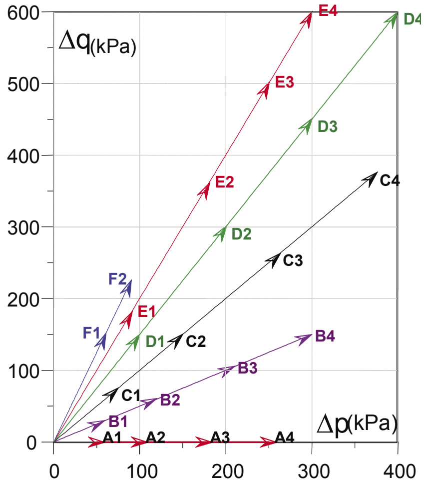

Figure 4. Isotropic and anisotropic compression stress paths at different ratios (Gomes Correia et al. 2001)

The loading test programme is fully described in Gomes Correia et al. (2001). Figure 5 shows typical global stress-strain relation with five very small unload/reload cycles at several stress states obtained from a test on the original material (0/31.5). Unload/reload cycles were applied during otherwise global unloading to minimise the effects of viscous deformation on the measured behaviour.

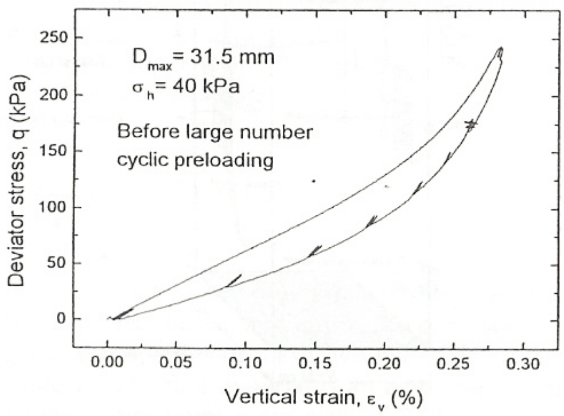

Figure 5. Overall stress strain curve with very small load-unload cycles (Gomes Correia et al. 2001)

Figure 6 shows a typical result from a very small vertical cyclic loading test at an anisotropic stress state. It may be seen that the unload-reload cycles are nearly closed hysteresis loops. The Young's modulus E_v, defined as $(d\sigma'_v/d\varepsilon_v)d\sigma'_h=0$, was obtained from linear regression of the respective stress-strain curve.

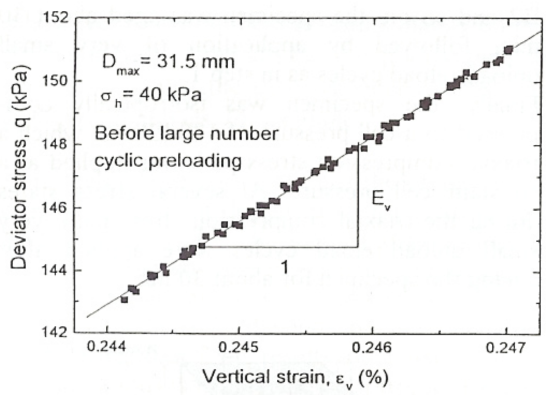

Figure 6. Typical vertical stress and vertical strain relation obtained during very small vertical stress path (Gomes Correia et al. 2001)

This same loading history was applied again after applying to the specimen 21,000 cycles of a constant deviator stress amplitude (around 230 kPa) along the triaxial compression stress path at a confining pressure of 40 kPa (as shown in Fig. 3, stress path D1-D5). However, it must be referred to that an accidental triaxial extension loading to an axial strain of -0,3 % took place before applying this large number of cycles. This allows an interesting finding reported hereafter.

In this paper, only results from analysis of the E_v values are reported, which is the key reference parameter for the material behaviour at larger strains, in particular when the ratio of inelastic to total strain increments is very small due to high compaction and also cyclic pre-straining.

3 YOUNG'S MODULUS STRESS DEPENDENCY AT SMALL STRAINS

The vertical Young's moduli, E_v, obtained from vertical unload-reload cycles with a very small strain amplitude (of the order of 0.001%) applied at various isotropic and anisotropic stress states were plotted against the respective vertical stress (σ_v) at which the E_v value was measured. A typical result is shown in Fig. 7 for material 0/31.5. It may be seen that, within a wide range of anisotropic stress states, the quasi-elastic stiffness in one direction (i.e., E_v) is essentially a unique function of the stress in the same direction (i.e., σ_v), while it is rather independent of the other orthogonal stresses (i.e., σ_h). It seems that the effects of cyclic pre-straining on the Young's moduli are practically negligible for the range of stresses shown. These results were also confirmed by the test results on the scaled material (0/12.5) and are consistent with the following hypo-elastic model (Tatsuoka & Kohata 1995; Tatsuoka et al. 1999a, b):

$$\frac{E_v}{f(e)} = \frac{E_{vo}}{f(e_o)}\left(\frac{\sigma_v}{\sigma_o}\right)^{m_z} \quad (1)$$

where σ_0 and e_0 are the reference stress (100 kPa) and void ratio; and E_{v0} and m_z are the material parameters. In our analysis, no correction was made for void ratio variations, since, when based on empirical equations for f(e) found in the literature, the corrections were insignificant, if any, while the confident correction was not possible as the formula for these very compacted materials having very low void ratio had not been obtained.

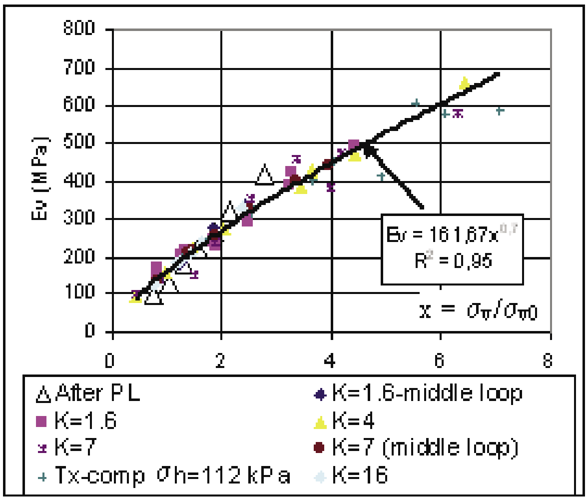

Figure 7. Vertical Young's modulus of the 0/31.5 material during first triaxial compression tests (Tx) and anisotropic compression (K) and after preloading (PL)

4 "S" SHAPED STRESS-STRAIN UNDER TRIAXIAL COMPRESSION

Gomes Correia (2004) reported that, opposite to the trend of significant decay in the stiffness with an increase in the strain usually observed with soils, with very compacted well graded unbound granular materials as tested in this study, both secant and tangent moduli increase with an increase in the strain until the strain becomes a certain level (Fig. 8). In fact, at small and intermediate strain level during global triaxial compression loading and unloading, the materials exhibit very small irreversible (or inelastic) strains, practically negligible compared to the elastic strains. Under this circumstance, it is naturally anticipated that the tangent and secant moduli (in particular the former) increase with an increase in the vertical stress during triaxial compression at constant confining pressure following Eq. 1. This trend of behaviour has been observed also with cyclic pre-strained Toyoura and Hostun sands (Tatsuoka et al. 1995, 1999a).

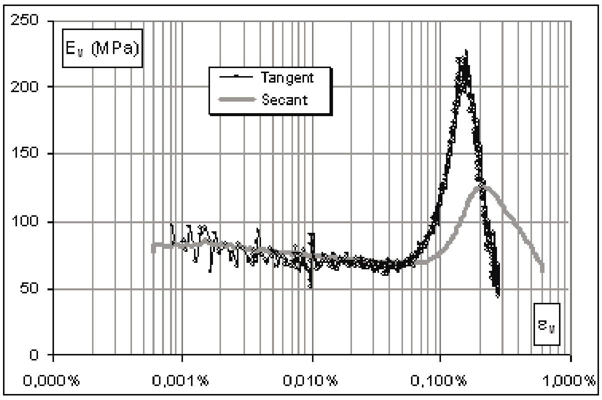

Figure 8. Tangent and secant moduli as a function of strain level for a very dense compacted granite 0/31.5 (Gomes Correia, 2004)

The previous experimental results that are available to the authors as well as those from the present study show that a very dense compacted unbound granular material (UGM) that has been subjected to a cyclic preloading history representative of traffic load exhibits a modulus versus strain curve typically with a shape as presented in Figure 8. The curve starts with an approximately plateau, where the modulus is practically independent of strain, followed by a substantial increase of modulus until the strain becomes around 0.5 %. This trend of behaviour is due essentially to an increase in the vertical Young's modulus, E_v, associated with an increase in σ_v, and can continue until the dilatant behaviour due to relative rotation of particles with slipping becomes significant. This trend of stiffness corresponds to a S-shaped stress-strain relation when subjected to unloading and reloading with a relatively large stress amplitude. Subsequently, the material starts showing a significant reduction in the stiffness with an increase in the strain as a consequence of an increase of irreversible (or inelastic) strain at an increasing rate with an increase in the strain. This result shows that, to obtain a normalised decay relation (i.e., an E_{tan}/E_{max} – log(ε_v) curve) representing the non-linearity only by strain increase, it is not relevant to normalise the respective measured E_{tan} value by being divided by the initial value of E_v (when at ε_v= 0), E_{max}, as reported by several other authors. Indeed, the E_v value at ε_v=0 is not the maximum value for the E_{tan} values but is the minimum value of the E_v values for the subsequent triaxial compression loading history.

Figure 9 shows for the 0/31.5 material the stress-strain relation during cyclic loading with several deviator stress amplitudes (stress paths D1 to D5 in fig. 3) along the triaxial compression stress path at a confining pressure of 40 kPa, which was performed after the pre-straining history involving a number of loading cycles equal to 21.000 with a constant deviator stress amplitude of 230 kPa. This trend of behaviour has reconfirm the previous results observed by Gomes Correia (2004) in the same material, but with different triaxial apparatus, as well that one also observed with cyclic pre-strained Toyoura and Hostun sands (Tatsuoka et al. 1995, 1999a).

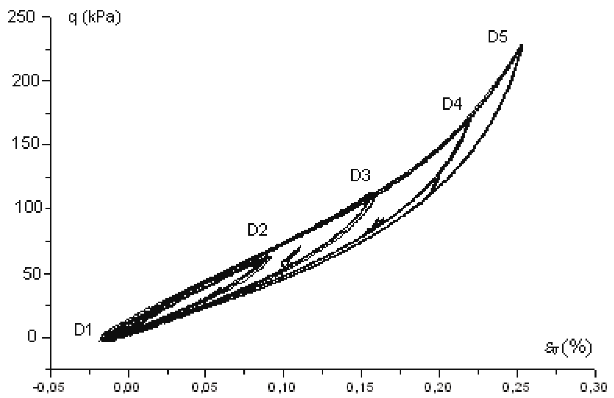

Figure 9. Stress-strain relation of the 0/31.5 material during cyclic loading with several deviator stress amplitudes along the triaxial compression stress paths at a confining pressure of 40 kPa (stress paths D1 to D5 in fig. 3), after a preloading of 21.000 cycles with a constant deviator stress amplitude of 230 kPa

It is very interesting to note that, in the first cycle of preloading, following the accidental triaxial extension loading, the loading stress-strain curve exhibited a very soft behaviour having a similar shape as with usual soils that has not been subjected to cyclic pre-straining (i.e., a consistent decrease in the tangent Young's modulus with an increase in the deviator stress; i.e., with an increase in the axial strain). This trend of behaviour is a consequence of relatively large inelastic strains that took place during the first cycle, as can be clearly seen in Fig. 10, as a result of damage to the micro-structure by accidental triaxial extension loading.

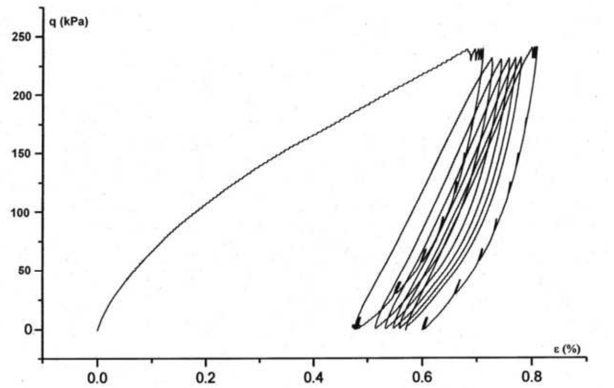

Figure 10. Stress-strain behaviour under cyclic loading, showing large inelastic strains during the first cycle, following the accidental triaxial extension loading

5 CONCLUSIONS

The following conclusions can be derived from the triaxial test results of very compacted crushed unbound granular materials presented above:

1) The effects of recent strain history (including cyclic pre-straining) on the small strain Young's modulus are practically negligible.
2) The vertical small strain Young's modulus is essentially a unique function of the stress in the same direction while it is rather independent of the other orthogonal stresses.
3) Both tangent and secant Young's moduli during global reloading of triaxial compression increase with an increase in the strain until the plastic strain rate starts significantly increasing, which was at a vertical strain around 0.5 %.

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