SUBGRADE EQUILIBRIUM WATER CONTENT AND RESILIENT MODULUS FOR UK CLAYS
DEGRE D'HUMIDITE DE SOUS-COUCHES A L'EQUILIBRE ET MODULE DE RESILIENCE DANS LE CAS D'ARGILES
CONTENIDO DE AQUA SUBTERRANEA DE EQULIBRIA Y DE RESTITUCION PARA ARCILLAS EN EL REINO UNIDO

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ABSTRACT: The main functional requirement of the subgrade is to resist excessive deformations during construction and in service. Deformation is controlled by ensuring adequate foundation resilient modulus. UK pavement design currently relies upon the determination of long-term CBR values for subgrades, which results in conservative pavement foundation design. To allow more realistic design an analytical approach is required, including measured values of resilient modulus at anticipated short- and long-term equilibrium subgrade water contents. Resilient modulus is determined from repeated load triaxial tests with on-sample strain measurement. Results from these tests on samples adjusted to model the subgrade behaviour at various design conditions are presented. These results are discussed, highlighting problems both with measuring small strains on undisturbed soils and in predicting and modelling accurately long-term soil behaviour.

RÉSUMÉ: Le critère principal d'une sous-couche est de résister à des déformations excessives en construction puis en service. La conception des chaussées au Royaume-Uni est actuellement basée sur la détermination de l'indice portant Californien (CBR) à long-terme des sous-couches. Pour une conception plus réaliste, il est nécessaire d'adopter une approche prenant en compte des valeurs de module de résilience mesurées à des degrés d'humidité de sous-couches à l'équilibre simulés à court et long-terme. Le module de résilience est déterminé à partir d'essais répétés en charge triaxiale avec mesure des contraintes sur l'échantillon. Dans cet article les résultats de ces tests sur des échantillons simulant le comportement de la sous-couche sous diverses conditions de conception sont présentés. Ces résultats sont discutés, en soulignant les problèmes résultant de la mesure de faibles contraintes sur des sols non-perturbés, et dus à la prédiction et à la modélisation du comportement des sols à long-terme.

INTRODUCTION: An empirical, approach based on California Bearing Ratio (CBR) has traditionally been used to design pavement foundations in the UK. Either insitu CBR tests on undisturbed subgrade (which do not allow for any future change to the subgrade) or laboratory CBR tests on remoulded samples of the subgrade are typically used. The latter include the conservative soaked CBR test, which usually results in considerable over design.

A better approach is via analytical design and performance specification. Loughborough and Nottingham Universities and Scott Wilson (PE) Ltd. are undertaking research on behalf of the UK Highways Agency to produce a performance specification for subgrade and capping to facilitate such an improvement. For performance based design, an estimation of the subgrade stiffness is required which incorporates in its calculation the environmental and load conditions experienced by the subgrade at various stages during the life of the pavement. Such a test will inevitably be laboratory based and must be able to simulate adequately the cyclic loading caused by the passage of a wheel.

The most applicable test method currently available to model this type of loading on recovered/manufactured samples is the Repeated Load Triaxial Test (RLTT). A series of such tests has been undertaken using equipment developed by Nottingham University.

Due to the (beneficial) effects of partial saturation on the stress-strain relationships for the cohesive soils typical of UK subgrades, it is necessary to conduct such tests under anticipated water conditions during the pavement's life. Attempts have therefore been made to prepare samples, that simulate the conditions that a subgrade may experience as part of a pavement foundation namely:-

- Undisturbed soil, as found in the base of cuttings at the time of construction,

- Remoulded, recompacted soil at insitu water content, as found in embankments at the time of construction,

- Samples in the two conditions above but at their equilibrium water content, which is often only achieved well after construction.

The aim of this paper is to report some of the findings from the RLTT programme on the predominantly cohesive subgrades found in the UK. It details how the equilibrium water content can be predicted, describes the difficulty of satisfactory sample preparation and highlights the problems of accurate data collection at the low stress/small strains which are characteristic of subgrades beneath trafficked pavements.

PREDICTION OF SUBGRADE EQUILIBRIUM WATER CONTENT: Equilibrium water content (W_{eqm}) is reached after the equilibration of (usually dissipation of negative) pore water pressures, the value being defined by the soil properties, stress history, position relative to the water table, efficacy of subsurface drainage and in certain circumstances environmental effects such as temperature, humidity and rainfall. This equilibrium value, once attained, remains relatively stable under impermeable pavements. Equilibrium water content (W_{eqm}) can therefore be used as a long-term design subgrade water content.

There are three main methods of predicting W_{eqm}:-

- Prediction from soil suction data, based on the position of the water table and soil plasticity(LR889; Black and Lister, 1979),

- Thornthwaite Moisture Index, which uses climatic data to define soil water content based on soil moisture deficit (Russam and Coleman, 1961). It is particularly useful for conditions where the water table is below the presumed zone of influence (approximately 6m for clays and 1m for sands) although it is not particularly applicable for temperate climates such as that of the UK.

- From field investigations of the water contents under exiting pavements for similar types of subsoil. Because of the specific nature of the information, this method is only applicable for adjacent construction/reconstruction.

According to the LR889 method, predicted suctions are used to estimate the subgrade equilibrium water content from a wetting or drying curve normalised for the soil's plasticity. The equilibrium water content is then empirically related to CBR for the particular soil plasticity. This method for predicting CBR is included in the current UK Pavement Design Manual (HA25/94; 1994) and has therefore been investigated in this study for inclusion as a predictive method of equilibrium water content, to be used in sample preparation.

SAMPLE DESCRIPTION: Manually driven 100 mm diameter (U100) samples have been taken from various trial and live sites where other fieldwork has also been undertaken.

Most RLTTs have been on undisturbed samples from a trial site at Hathern, Leicestershire UK. Nine U100 samples were taken from an area 5m wide by 30m long. The soil consists of a firm/stiff sandy silty CLAY, with silt partings, the clay becoming more sandy with depth, overlying a wet silty sand. Samples were taken above the interface of the clay with the sand. The Atterberg Limits (LL=27-36%, PL=15-20%) and natural water content (W_{nat}=15-23%) were used to predict (W_{eqm}=10-16%).

Samples from the A1(M) motorway, near Peterborough UK, consist of Oxford CLAY (LL=40%, PL=25%, W_{nat}=21.5%, W_{eqm}=24.3%), with some fine (2-6 mm) gravel and occasional stones (20-25 mm). A further field trial site at Bardon, Leicestershire UK, comprises a firm slightly gravely sandy silty CLAY with silt partings (LL=46%, PL=22, W_{nat}=19%, W_{eqm}=23%).

SAMPLE PREPARATION AND TEST PROCEDURES: The RLTT equipment used was developed to form a prototype for a possible commercial test apparatus (Cheung, 1994). It requires samples of 100 mm diameter and 200 mm long. The samples are fitted with two on-sample strain measurement loops which measure the vertical strain over the middle third of the sample in order to remove end restraint effects caused by the load platens. These on-sample strain gauges are attached to cruciform studs that are pressed into the sample. The resilient strain is reported as the average of the readings from the on-sample gauges. A linear variable differential transformer (LVDT) is fitted to the top load platen to measure total sample strain. Radial proximity transducers are used to measure radial strain. The sample is tested with an applied cell pressure of 20 kPa to simulate the confining stress beneath a typical road pavement structure and subjected to an axial seating stress of 5 kPa. The samples are loaded at increasing levels for each set of 1000 cycles (at 10 kPa increments) applied at a frequency of 2 Hz. At 5% cumulative permanent strain the cyclic loading is stopped and the sample is loaded monotonically to failure. The resilient modulus is calculated from the 999th cycle of each load increment, with the final 10 cycles of each increment being investigated to ensure that the 999th cycle is representative.

To allow direct comparison with field conditions the samples are tested without preliminary conditioning, as is used in other resilient modulus tests (AASHTO, 1992). Conditioning loads applied to samples affect the sample stress-strain behaviour, and thus the modulus. In practice the subgrade will be subjected to compaction and trafficking stresses during construction, although these are difficult to predict. An arbitrary conditioning sequence was thus considered inappropriate for this research.

The *undisturbed* sample was initially trimmed directly from the U100 samples and tested. The *remoulded* sample was prepared from soil broken up in a mixer until it formed lumps of less than 5 mm, before being compacted according to BS 1377 (BSI, 1990) in a 100 mm diameter, 250 mm high Procter compaction mould in five equal layers using a 2.5 kg hammer falling through 300 mm, 27 blows being applied to each layer.

In order to obtain samples that accurately represent the equilibrium condition the prepared sample (either undisturbed or remoulded) should be allowed to change water content at the equivalent conditions of confinement and suction that would be experienced in the field. Various authors have proposed methods of forcing water into pre-compacted (i.e. remoulded) samples (Chu et al, 1977; Drumm et al, 1997). They state that the soil requires a considerable time to equilibrate, even for high permeability soils. Subgrades in the UK are typically low permeability cohesive soils and for a commercial test, as would be required to give data for a performance based design, such a lengthy procedure would prove impractical. The difficulty of bringing undisturbed samples to equilibrium would be greater. in addition, it has been found that when water was forced radially into a clay under a back pressure in an attempt to reduce the preparation time, considerable softening of the outside of the specimen occurred with very little water penetration (i.e. an even water distribution could not be achieved).

For this reason it was decided to add sufficient water at the time of remoulding to bring samples to W_{eqm}, although it was appreciated that sample behaviour would be different than if the samples had been remoulded and then brought to equilibrium. The primary reason for this is that addition of water will affect the compaction of the remoulded samples. Nevertheless it was hoped that this remoulding to equilibrium, as is allowed for in conventional CBR design, would be a worst case equilibrium condition for design because of destruction of the soil structure, while producing a commercially practical test.

Therefore for this investigation no 'equilibrium insitu' samples were created by allowing undisturbed U100 samples to wet up to W_{eqm}. The *equilibrium remoulded* sample was manufactured by mixing the amount of water predicted from LR889 (Black and Lister, 1979) into the remoulded sample prior to compaction, as described above.

EXPERIMENTAL RESULTS: There have been several problems that have become apparent with the use of the RLTT for design, specifically those relating to:

- material variability for sampling,
- low strain measurement in the triaxial test (both due to material variability and instrumentation),
- prediction of equilibrium water content for mixed soils, and
- preparation of uniform samples which adequately model the insitu subgrade conditions.

Figures 1 and 2 present RLTT data from the nine samples taken from the Hathern field trial site. These show that, despite

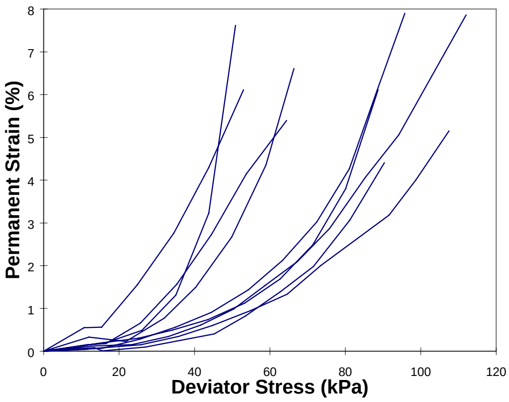

Figure 1. Permanent Strain against Deviator Stress from RLTT for Nine Undisturbed Samples from Hathern.

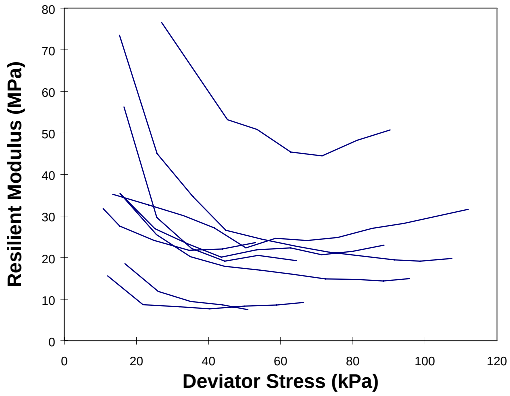

Figure 2. Resilient Modulus against Deviator Stress from RLTT for Nine Undisturbed Samples from Hathern.

the small plan area from which the samples were taken, the variability of the materials leads to significant differences in observed behaviour. The soil from visual inspection, however, was considered to be similar over the entire area. Figure 2 highlights better this variability as the calculation of permanent strain is less sensitive to instrumentation error than the calculation of resilient modulus. This soil variability has been observed for all sites that have been tested in this project.

Figure 3 shows typical sets of resilient modulus data for two undisturbed soils tested in the RLTT. The curves show the data from the three strain measuring devices to be variable. The Hathern data

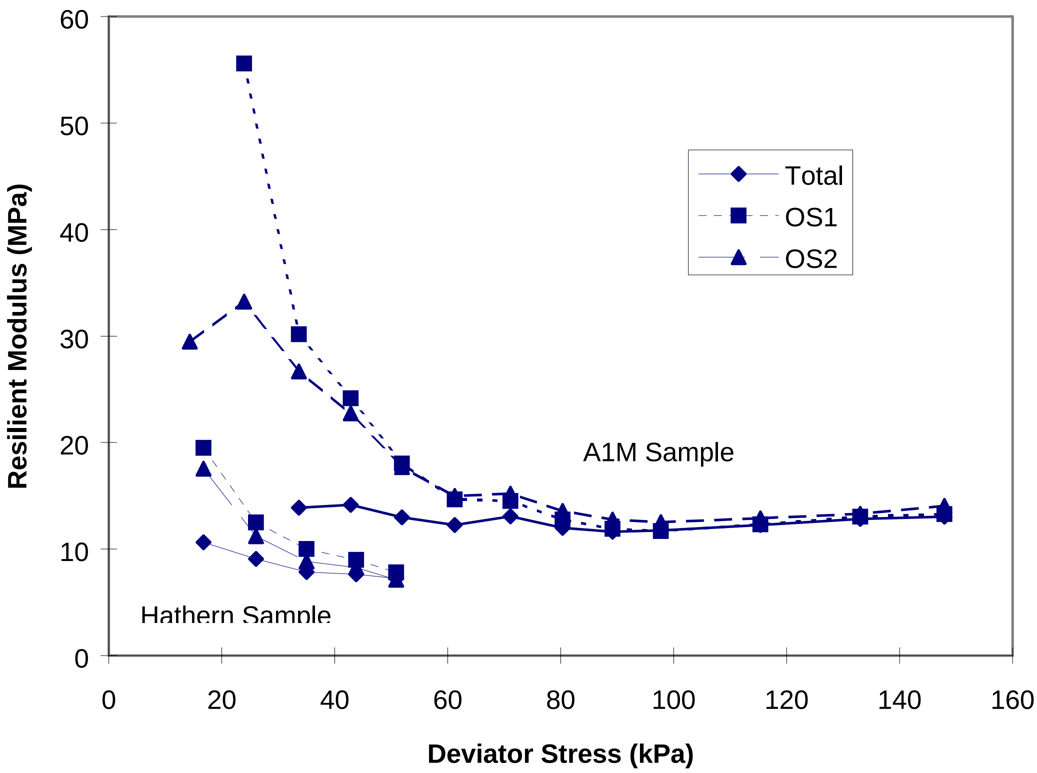

Figure 3. Resilient Modulus Against Deviator Stress for two Undisturbed Samples. The Moduli have been Calculated from the Two On-Sample Measuring Loops (OS1 and 2) and Total Sample Strain.

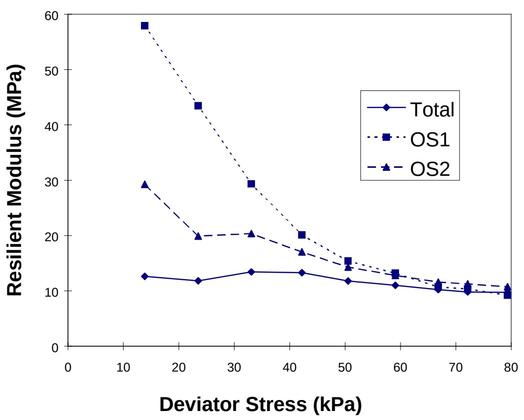

Figure 4. Resilient Modulus against Deviator Stress for a sample from Bardon that has been Remoulded at its Equilibrium Water Content.

are broadly as expected, with the two on-sample strain gauge curves (OS1 and OS2) showing similar trends although slightly different values. This difference is probably due to slightly different material behaviour across the sample. The curve for resilient modulus determined from the total sample strain lies below those of the on-sample strain gauges, indicating that the strains were greater. Conventional thinking would suggest the reverse, i.e. that the strain in the middle portion of the sample would be greatest due to the lack of restraint from the load platens. However at low stress the deformation caused to the sample is very small and is extremely sensitive to areas of lower stiffness, such as could occur due to disturbance at the ends of the sample during sample preparation. At higher stress, after high permanent strain, the moduli calculated from the transducers converge to form a stiffness asymptote.

The A1(M) sample shows significant variability across the sample at low deviator stresses. This sample contained evidence of gravel and voids along one side, which is likely account for the large differences in stiffness at low stress. In addition the majority of subgrade soils are partially saturated. At low strains, therefore, it is possible that the resilient behaviour of the samples (and hence the deflection induced) will be influenced by compression of the air in voids.

Figure 4 shows equivalent strain gauge data for a Bardon sample that was remoulded at its equilibrium water content. Similar trends are apparent. It should be noted that the studs used to connect the strain gauges to the sample are pushed in, which results in some local disturbance. Where the sample contains gravel, as at Bardon, significantly greater internal sample disturbance will occur if the studs hit the gravel particles during insertion, possibly also resulting in a poor connection between the sample and the strain gauge loop. As the sample sustains permanent deformation the soil will consolidate around the studs and improve the fixing of the strain gauges. The use of conditioning, if carried out at a high enough stress, would remove these connection and end disturbance errors, although the conditioning will also affect the sample response. It can be shown that reasonable agreement in instrumentation output is reached at resilient strain levels (i.e. greater than approximately 0.3%) for both Bardon and Hathern specimens, but that material variability (figure 2) is independent of strain level.

The prediction of W_{eqm} presents significant problems for mixed soils, since it is based on the measured plasticity. For soils that contain a granular fraction, which is removed for the plasticity tests, the calculation of W_{eqm} is distorted. For example, W_{eqm} for the Hathern samples predicted from LR889 (Black and Lister, 1979) produces a value lower than the undisturbed value.

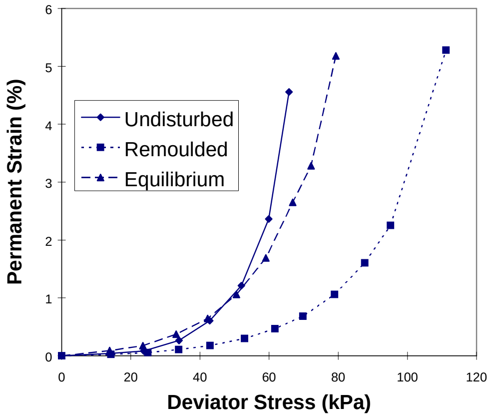

Figure 5. Permanent Strain Against Deviator Stress for a Sample from Bardon Prepared in Three Different States (Average of On-Sample Strain Loop Readings).

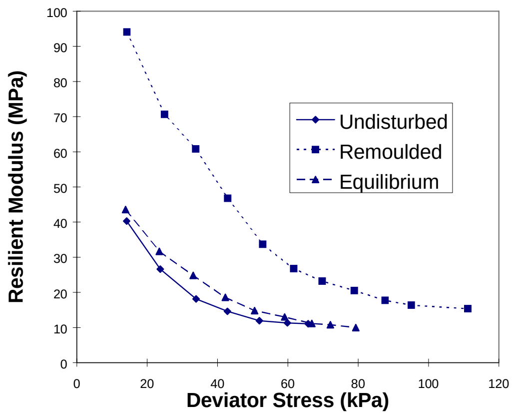

Figure 6. Resilient Modulus Against Deviator Stress for a Sample from Bardon Prepared in Three Different States (Average of On-Sample Strain Loop Readings).

Figures 5 to 8 show the behaviour of two samples prepared in the three states described above (note 'equilibrium' = *equilibrium remoulded*). The Bardon sample (Figures 5 and 6) contained a number of wet silty bands. When the soil was remoulded these weak zones were redistributed through the sample resulting in a significant improvement in overall sample strength and stiffness. When the additional water to reach W_{eqm} is added the sample strains increased as would be expected, in this case to the level of the undisturbed sample. If the change in water content had not been combined with a destruction of the soil structure (i.e. a wetted undisturbed sample had been created) it is likely that the sample would have exhibited a lower resilient modulus than the mixed soil.

The A1(M) sample had a more homogenous clay structure. Figures 7 and 8 show that the remoulded sample behaves similarly to the undisturbed sample. The equilibrium sample shows a reduction in modulus, as expected. In this case the remoulded sample exhibits similar permanent strain but lower resilient strain (thus higher modulus) than the undisturbed sample. In this latter respect the behaviour again contradicts conventional thinking. This is probably a result of the destruction of fissures which can be found in the natural soil.

CONCLUSIONS: In order to allow a performance based approach to pavement foundation design to be implemented a test is required to measure resilient modulus of the subgrade at expected equilibrium conditions. The RLTT appears to be the most appropriate. However testing has revealed significant problems.

Small strain measurements at low applied deviator stresses result in significant problems in unconditioned samples. The calculation of modulus at low stress is highly sensitive to small differences in strain, which leads to large apparent variation between test data.

Soil variability results in difficulties in obtaining representative design values, not only between test samples, but also across any one sample.

Remoulding and recompaction of soil leads to a destruction of soil structure. This can redistribute weak or strong materials and water within an homogeneous sample, which affects compaction and subsequent test behaviour.

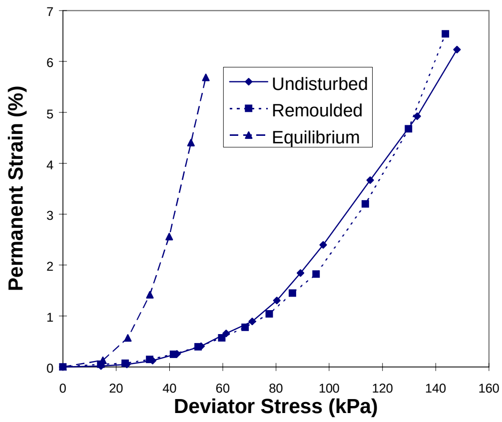

Figure 7. Permanent Strain Against Deviator Stress for a Sample from A1(M) Prepared in Three Different States (Average of On-Sample Strain Loop Readings).

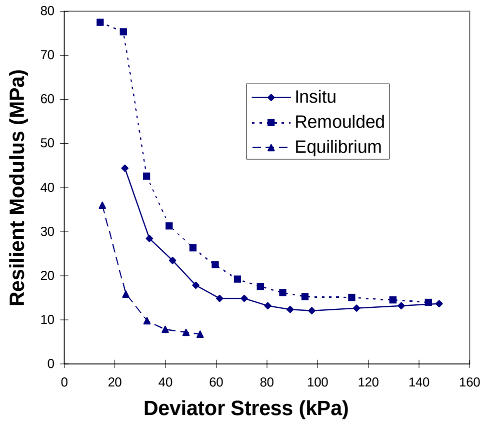

Figure 8. Resilient Modulus Against Deviator Stress for a Sample from A1(M) Prepared in Three Different States (Average of On-Sample Strain Loop Readings).

It is evident, therefore, that a suitable method of varying the water content of soil to represent dissipation of suctions in in-service pavement subgrades is required for routine testing, as well as a suitable method of predicting change in water content over time. The method chosen must be such that it does not cause an (unrealistic) improvement in properties, in mixed or fissured soils.

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