Comparative Study of Laboratory Based Methodologies for Determination of the Resilient Performance of Clay Subgrades

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ABSTRACT: For the development of performance-based design for pavement foundations appropriate laboratory assessment of the underlying subgrade is required. To achieve this, assessment of the resilient behaviour (stiffness) and resistance to permanent deformation of the subgrade must be made, under realistic loading conditions. This paper compares data from variably confined repeated load tests (utilising the recently developed "Springbox" apparatus), simplified repeated load triaxial tests (using standard triaxial apparatus) and repeated load triaxial tests. Tests were undertaken on a series of remoulded clay subgrade materials for a range of water contents prepared between the plastic limit and a predicted long-term equilibrium value. Correlations of the resilient deformation (stiffness) measured in the various tests are presented, together with comments on their applicability for pavement design. Having accommodated the differences in the confining stress, acceptable comparisons between the data from the various devices are achieved. However, the quality of the resilient data from the simplified procedures was affected by the resolution of instrumentation, producing better correlations at higher applied stresses where the stiffness approaches a constant value termed the "stiffness asymptote". A correlation between stiffness asymptote and sample plasticity is also presented. To conclude, the suitability of the various test devices is discussed and outstanding design/sample preparation issues considered. Significantly this includes the need to predict and manufacture samples representative of long term (equilibrium) subgrade water contents.

KEY WORDS: Subgrade, Laboratory Testing, Resilient Stiffness

1 INTRODUCTION AND BACKGROUND

Performance of pavement subgrades can either be assessed on the basis of past experience and empirical relationships, or by undertaking more fundamental testing. Simplistic index and relationship tests, in particular the California Bearing Ratio (CBR) for pavement foundation layer design, have been empirically correlated with acceptable pavement performance over a number of years and still form the basic of UK pavement foundation design (DMRB, 1994). However, it is widely recognised that the CBR does not measure the fundamental performance parameters required of a pavement foundation or subgrade (Brown, 1996), namely the resilient stiffness and resistance to permanent deformation (which is key to the phenomenon of rutting). Ideally, for a laboratory test, these two parameters need to be assessed concurrently under loading and environmental conditions similar to those they will experience in the field. This leads to two main design conditions, a short term condition when high stresses from construction vehicles are applied directly to the foundation, and a longer term in-service condition where the applied stresses to the foundation from traffic are lower, (due to the presence of the structural pavement above), but the water content of the subgrade may be higher due to equlibriation of pore water pressures i.e. a subgrade equilibrium water content.

Once the performance of the materials has been established for these conditions a suitable design system needs to be used to assess required pavement thickness based on controlling an allowable permanent deformation within the foundation and subgrade. Such a system must include the changes in the environmental conditions and the materials stress dependency.

Advanced laboratory tests available for assessing both the above performance parameters for clay subgrades include the hollow cylinder apparatus (Brown, 1996), the soil rut testing facility (Cheung and Dawson, 1998) and the repeated load triaxial test (RLT). All have their limitations, mainly based on limits of the size of particles that can be assessed, and the need for on-sample instrumentation. For determining resilient stiffness the RLT is the most commonly available of these research type tests, however, it is generally excepted that even the RLT is not suitable as a routine test for commercial use due to its relative complexity (Kim et al, 2001). The laboratory assessment of resistance to permanent deformation is more complex than the determination of resilient stiffness. Only the hollow cylinder apparatus and soil rut test have the ability to apply the reversal of shear stresses that are experienced by materials under the passing of a wheel, and hence allow direct measurement of permanent deformation, under realistic loading and confinement conditions.

Historically, to overcome the complexity of precise performance testing, material specific relationships that correlate between more basic index parameters, such as subgrade plasticity, (related to soil suction), and undrained shear strength have been proposed. These are usually linked to pavement foundation performance via CBR. Further correlations have then been proposed that link to the required performance parameters of resilient stiffness and resistance to permanent deformation (for example Stiffness E= $17.6CBR^{0.64}$, E=10CBR or for permanent strain $q_{allow(t)}=0.5q_{max}$), however it is accepted all these correlations have their restrictions and are known to be insensitive (Brown, 1996).

More recently other correlations and simplified testing regimes have been proposed where resilience is measured directly for design, but the more complex resistance to permanent deformation is accommodated via a threshold stress approach (defined as the applied stress where the onset of permanent deformation increases exponentially, Figure 1), linked to shear strength (Cheung and Dawson, 1998, and Frost 2000). Cheung proposed the stress that causes 1% permanent deformation (after increasing increments of applied deviator stress) as a limiting of applied subgrade stress. More recently lower bound relationships between deviator stress, undrained shear strength (S_u) and threshold stress have been established for a broad range of UK clay subgrades (Frost et al, 2004 and Frost et al, 2005).

In this paper two such simplified test methods are presented and linked to laboratory repeated load triaxial testing. The first test utilises a pseudo-static triaxial (PST) testing procedure (Frost et al, 2005). The second is the Springbox test (SB), developed primarily to test granular pavement foundation materials (Edwards et al, 2004). Both of these tests aim to produce similar (direct) outputs of resilient stiffness to that from the repeated load triaxial test, and rely on correlations related to strength to enable permanent deformation to be accommodated in design. The aim of these two tests is not to replace the RLT, but to try and provide simplified practical alternatives, other than using more basic index tests, to allow routine assessment of the resilient performance of clay subgrades.

Results are presented from testing undertaken on remoulded samples of three clay subgrade materials over a range of moisture contents using both the simplified testing regimes, and parallel repeated load triaxial testing on similar samples to allow comparison between the methods.

2 SIMPLIFIED TEST METHODOLOGIES AND RATIONALE

2.1 Pseudo-Static Triaxial Test

The Pseudo-static triaxial tests are cyclic load tests performed in a standard triaxial test apparatus using a slow frequency of loading. The equipment and test capabilities are, therefore, significantly more limited in comparison to a repeated load triaxial apparatus. A number of researchers have proposed the use of standard triaxial apparatus to develop simplified pavement subgrade test procedures (Frost et al, 2005 and Kim, et al, 2001). The two main limitations of using standard triaxial apparatus to apply pavement type loadings are load pulse frequency and the resolution of the axial strain measurements. The first of these limitations is not considered to be a concern for the assessment of resilient behaviour, as no changes in resilient response with load pulse frequency have been observed over a frequency range of 0.01 to 10 Hz (Brown et al, 1975). The second limitation related to accuracy of strain measurements was avoided by aiming to measure the stiffness at higher stress (termed the stiffness asymptote). The stiffness asymptote, (see Figure 1), is defined as a relatively constant value of resilient elastic modulus (stiffness) being reached at relatively high deviatoric stress levels (Frost, 2000).

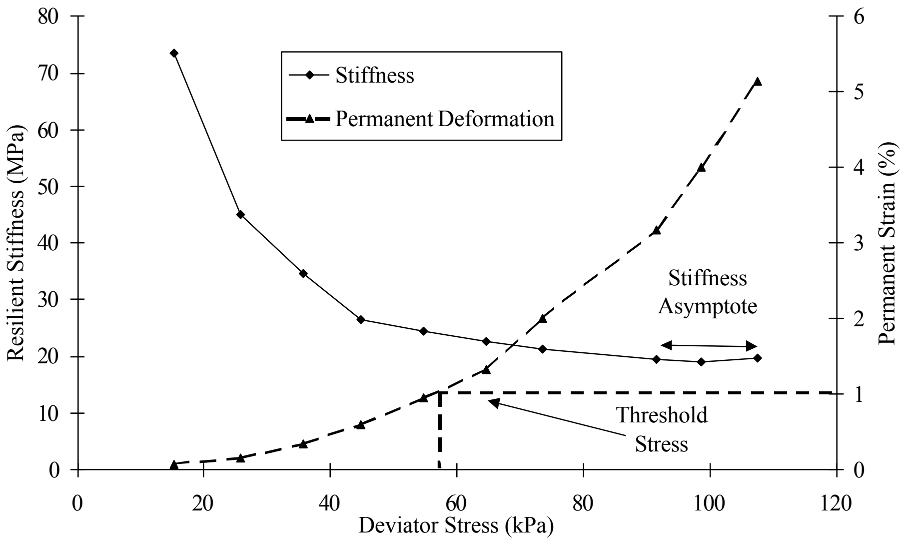

Figure 1: Typical relationship between resilient stiffness, permanent strain and deviator stress for a clay subgrade sample tested in a repeated load triaxial test (1000 cycles at each stress increment).

The use of a stiffness asymptote value within design, is valid as a worse case for inversely stress dependant cohesive materials, if the short term (construction condition) subgrade resilient stiffness at a high deviatoric stress, is lower than the in-service stiffness, under a low deviatoric stress but at a higher subgrade equilibrium water content (Frost et al, 2005). The pseudo-static testing (PST) procedure used was that defined by Frost et al, (2005). The method uses a standard 100 mm diameter monotonic triaxial apparatus with standard dial gauges and a proving ring for strain and stress determination. A confining stress of 20 kPa and a seating stress of 10 kPa were applied to the sample. The cyclic loading comprised 5 pulses of load/unload applied (at a load rate of 5 mm/min) at each cyclic stress increment, starting at 10 kPa, and increasing in 10 kPa steps until 5% permanent strain was sustained. The sample was then monotonically loaded, to failure (defined as either the peak deviator stress or 20% strain) to assess the undrained shear strength (S_u). Therefore, the testing was strain-controlled (i.e. the time to reach the specified target cyclic stress was material dependent). The tests were undrained, and area correction for applied stress using the normal fixed volume assessment was applied.

2.2 The Nottingham Asphalt Tester (NAT) Springbox Test

The Springbox test (Edwards, et al 2004) is a variably confined repeated load test, primarily manufactured to determine resilient stiffness and a relative measure of permanent deformation for unbound and weakly bound granular materials of less than 40 mm particle size (Figure 2). The tests applies a vertical load to a 170 mm cubic specimen and allows horizontal strain of the specimen on one axis, with the sides restrained by springs, the other horizontal axis is fully restrained.

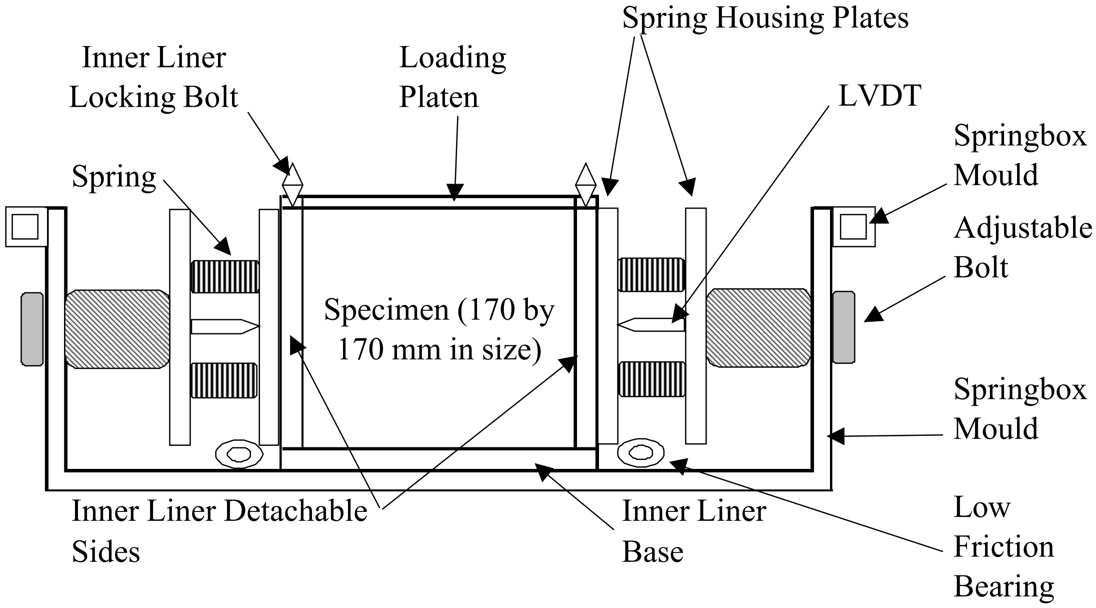

Figure 2: Schematic cross section lengthways through the Springbox testing apparatus.

The apparatus uses a standard Nottingham Asphalt Test load frame. A sinusoidal pulse of load was applied at a frequency of 1 Hz. The following test procedure was applied to all the specimens tested; apply 500 cycles at a low cyclic stress level (37 kPa), apply the same number at an intermediate cyclic stress level (92 kPa) and repeat at a high cyclic stress level (162 kPa). An 8 kPa seating stress was applied to the samples throughout testing. Further details on the development of the test are presented in Edwards et al, (2004). The results are expressed in terms of resilient stiffness taken as an average from the last 5 cycles. It is not currently possible to measure shear strength in this test.

The Springbox results have been analysed initially by making the simplistic (but practical) assumption of linear elasticity (Edwards et al, 2005). The vertical applied stress, vertical strains (transient and permanent) and horizontal strains are all measured. A known spring rate and an experimentally determined wall friction coefficient (*cf*) are used to calculate the horizontal confining stresses and Poison's Ratio (υ) to enable calculation of stiffness. However the friction and adhesion of the cohesive materials to the apparatus walls will influence the results. Methods to reduce this using "non-stick" material in the box were trialed, for ease of explanation this is described further in Section 4.3.

It should be noted that when comparing the results from the Springbox to other tests that the adopted Springbox test procedure uses bulk stress values within the stiffness asymptote range of the triaxial tests. These data will therefore not allow comparison of data at low deviator stress.

2.3 Repeated Load Triaxial Test

Repeated load triaxial testing was used to act as a reference test. This was performed in a servo controlled pneumatic repeated load triaxial apparatus using 100mm diameter samples. Sample strains were measured with an axial LVDT and two on-sample Hall Effect Transducers fixed over the central 80 mm length of the specimen. A confining stress of 20 kPa and a deviatoric seating stress of 10 kPa were applied and the samples loaded with sinusoidal deviator stress pulses at a frequency of 2 Hz. Cycling started at a deviator stress of 10 kPa for 1000 cycles, and further burst of 1000 cycles of deviator stress were applied, increasing in 10 kPa steps, until 5% permanent sample strain was sustained. The on-sample gauges were then removed and the sample was monotonically loaded to failure; the tests were performed undrained. Area correction for applied stress using the normal fixed volume assessment was used. The resilient stiffness and permanent deformation generated during the loading was calculated as an average from the last 5 cycles from each 1000 cycle burst.

3 MATERIALS, PREPARATION AND TESTING

3.1 Materials Used and Soil Classification Tests

Three clay soils were tested. Mercia Mudstone (MM), a medium plasticity clay, Oxford Clay (OC) a high plasticity clay and English China Clay (ECC), a quality controlled clay product with a high plasticity index. MM and OC were the two main materials tested. ECC was used for repeatability and reproducibility testing. The key parameters for these materials are summarised in Table 1.

Table 1: Summary of key material properties.

Material	2.5 kg Proctor		Plasticity Index	Plastic Limit (%)	Specific Gravity	Clay Content (%)
	Maximum Dry Density (Mg/m^3)	Optimum Water Content (%)				
MM	1.81	16.5	20	16	2.71	24
OC	1.48	17	23	32	2.51	42
EC	1.46	23	22.5	31	2.60	65

3.2 Sample Preparation

Compaction of samples for the triaxial tests used a method similar to the 2.5 kg Proctor compaction test (BS1377, 1990) but using 12 layers, 27 blows per layer to form a 300mm long sample from which a 200mm long triaxial sample could be taken. The Springbox samples were compacted using a vibrating hammer (due to the shape of the sample required) with a 90 by 90 mm compaction foot to a target density (defined from a 2.5 kg Proctor compaction test BS1377, 1990) and comparable to those used in the triaxial tests samples.

The water content of the samples were determined both prior to and following testing. Sample states were targeted across a range of water contents based upon the soil index properties of Optimum Water Content determined from compaction tests, Plastic Limit (PL), and Equilibrium Water Content (predicted using the Black and Lister, 1979 method), similar to that used to predict long–term water contents within current UK CBR based pavement foundation design.

Sample preparation at both extremes of the water content scale proved problematic, samples significantly dry of their plastic limit suffered from poor interlayer bonding (resolved to some degree by scarification of the layers prior to compaction of the next layer) and samples compacted significantly wet of their plastic limit proved difficult to compact and test, due to their relative softness.

4 RESULTS AND DISCUSSION

4.1 Undrained Shear Strength Tests

The undrained shear strength (S_u) determined following the cyclic loading element of the RLT and PST tests are shown plotted against sample water content in Figure 3. The shear strength results from both triaxial test methodologies appear similar indicating a good comparison between prepared samples can be made. This also suggests that the stress range used during cycling did not approach high levels relative to the peak deviator stress at failure. Additionally the comparability of data indicates that the strength measurements after repeated loading in the PST is comparable to that from the RLT suggesting that the strength derived correlations with threshold, from RLT data (described earlier) can be utilised with measurements from the PST.

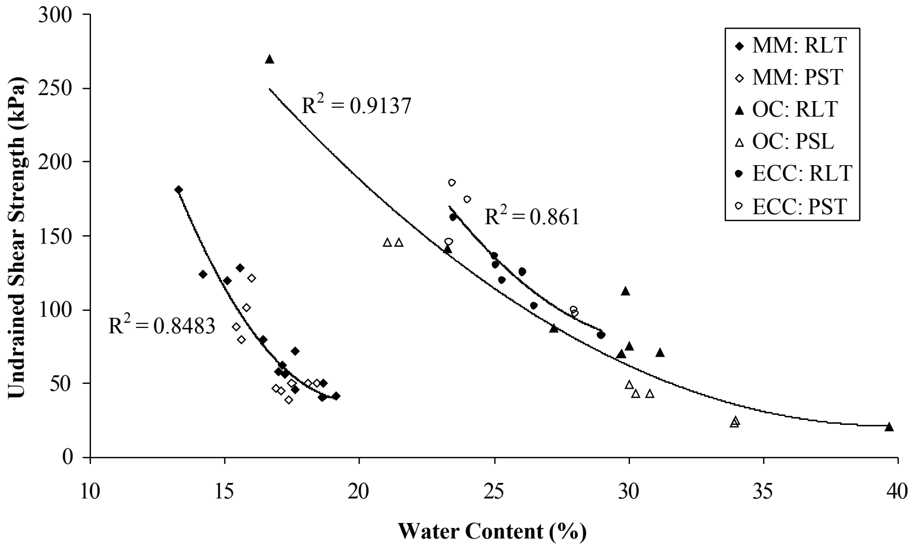

Figure 3: Relationship between undrained shear strength (S_u) and water content for three clay subgrade types assessed, measured in both repeated load triaxial tests (RLT) and pseudo-static triaxial tests (PST).

4.2 Triaxial Test Results

Comparison between data from the repeated load triaxial (RLT) with on-sample strain gauges and the pseudo-static triaxial test (PST) show the PST equipment to display some variability in measured resilient stiffness at low deviatoric stress levels, (Figure 4), primarily related to the resolution of the axial strain measuring instrumentation, (space precludes full discussion of this here, but these issues are further considered in Frost et al, 2005). However, with increasing deviatoric stress the measurements of resilient stiffness produce a consistent asymptotic stiffness value which correlates well between the two tests for measurements made with whole sample and on sample gauges, although the PST does assess a lower value of stiffness that RLT. This confirmed the expected relationships from earlier work (Frost 2000, and Frost et al, 2004).

Figure 5, shows the relationship between stiffness asymptote and sample water content normalised against the materials plastic limit. These data show good correlations to the curves of best fit and show a reasonable correlation between the two tests. Although the PST results lie below those from the RLT the two data sets start to converge at around the plastic limit. Typically optimum water content for compaction on site lies just above a soil's plastic limit. At equilibrium water content the prediction method used (Black and Lister, 1979) tends to predict long-term water contents in the range of 1.08 to 1.20 water content / plastic limit. Therefore, on the basis of this simple model the results indicate that the PST methodology is suitable for measuring resilient stiffness asymptotes, both under the short-term construction and longer-term in-service equilibrium conditions likely to be experienced in the field.

However, more significant is the apparent correlation of the lines of best fit and the pattern of the RLT data across the range of materials assessed. This curve indicates (as could be expected) a relationship between stiffness at high stress (approaching peak) and the materials plasticity. This could present a prediction method for soil stiffness, based on soil index properties similar to that currently allowed for assessing CBR from plasticity data in UK design. This CBR value is often used to calculate stiffness using the relationships defined in Section 1. Given the known insensitivity of the CBR this method may provide a more appropriate correlation for assessing a design stiffness where limited data are available.

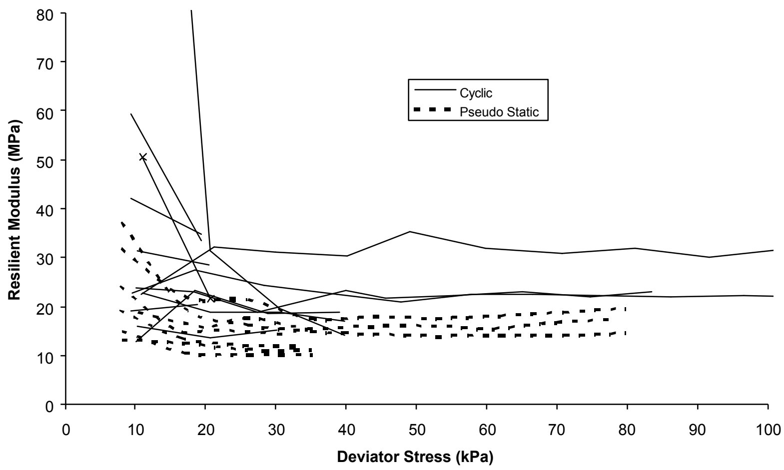

Figure 4: Typical Comparison of the Relationship between Resilient Modulus and Deviator Stress for both Pseudo Static and Cyclic Testing on Mercia Mudstone Samples.

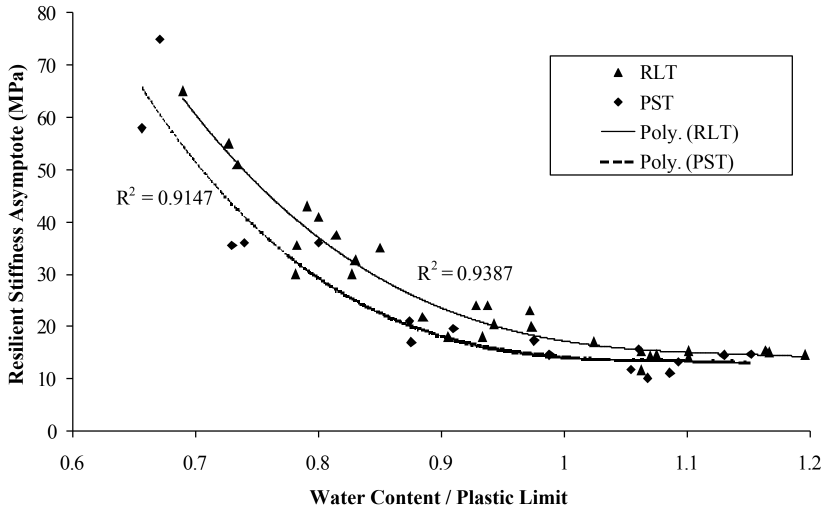

Figure 5: Relationship between asymptotic resilient stiffness and the ratio of sample water content to plastic limit for the repeated load (RLT) and pseudo-static triaxial tests (PST) for all the materials tested.

4.3 Springbox Tests

Figure 6 compares asymptotic stiffness values measured in the Springbox to comparable tests in the Repeated Load Triaxial Test. The results show a reasonable approximation between the asymptotic stiffness values, with similar trends shown. However, direct comparison of the results from the Springbox with the other test methods is not straightforward. Firstly, the Springbox has variable confinement in one horizontal direction only and is rigid in the other. This compares to a triaxial that applies a uniform confining pressure around the specimen. Here a bulk stress approach has been used to allow comparison between the tests (as shown in Figure 6). The second factor influencing comparison (interrelated to the first) is wall friction. The current simplified approach to the analysis (Edwards, et al 2005) incorporates a frictional stress (*cf* x normal stress) in the analysis. Figure 6 shows that using a *cf* of 0.38 (used in the analysis of MM samples, based on previous work on fine granular material) appears to overestimate the sample's resilient stiffness in comparison to the triaxial test. However, the trends of resilient stiffness against water content for the MM samples appear similar and the use of a revised *cf* of 0.70 results in a coincidental plot for both the triaxial and Springbox results (Figure 6).

Additionally, adhesion of the clay sample to the Springbox liner sides is also likely to be a significant contributory factor to the additional resisting forces/boundary condition effects of the test. Uniform adoption of this increased *cf* for adjusting future testing of clay materials is unlikely to be justifiable as adhesion is likely to be sensitive to clay mineralogy and sample water content. An alternative approach to eradicate adhesion was investigated on the Oxford clay samples using a combination of low friction lining materials (polytetrafluoroethylene and/or grease proof paper). The oxford clay (OC) samples (Figure 6) were tested using such friction reducing materials within the liner and on the underside of the loading platen. The results from these tests are encouraging, as again a similar trend to the repeated load triaxial testing is seen.

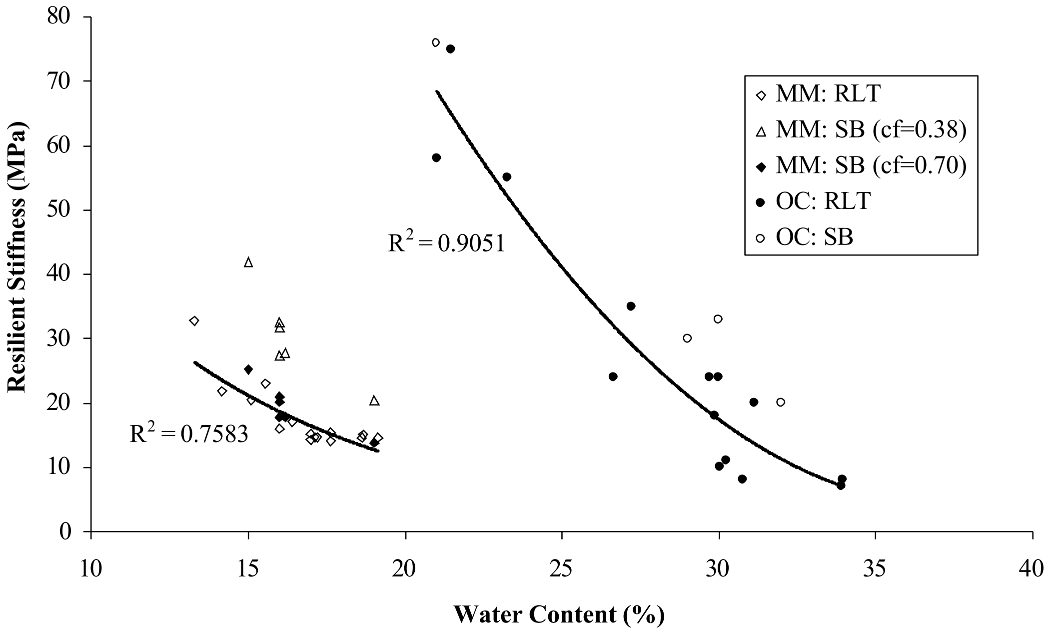

Figure 6: Repeated load triaxial and Springbox resilient stiffness results plotted against water content at comparable bulk stress values.

5 CONCLUSIONS

Two simplified testing procedures are presented to determine resilient stiffness values for clay subgrades over a range of water contents. The current assessment indicates that both tests are suitable for determination of the asymptotic resilient stiffness of clay subgrades.

The Springbox shows the potential of being able to determine resilient stiffness over lower deviatoric stress ranges than the pseudo-static triaxial test procedure, which perhaps would give added confidence in any subgrade assessment, but material specific issues of friction and wall adhesion in the Springbox must be considered to provide appropriate data.

The use of an asymptotic stiffness value within pavement design is valid if the short-term resilient stiffness design condition (at a relatively high deviatoric stress but low water content) is worse than that of the longer term in service stiffness at lower stress but higher equilibrium water content conditions. However, it is recognised that a number of factors require further work such as methods to predict the equilibrium water content changes in in-service pavements.

None of the tests replicates traffic loading conditions significantly well to assess permanent deformation data directly. However, by the use of correlations of threshold stress and subgrade undrained shear strength, it is perhaps possible to accommodate an assessment of the onset of significant permanent deformation within pavement design from the simple tests.

Correlation between asymptotic stiffness and normalised water content to material plastic limit is presented. This correlation appears to potentially offer a better assessment of subgrade stiffness than the frequently used assessment of CBR from plasticity data and then correlating CBR to stiffness, which many authors consider insensitive and inappropriate.

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