The Routine Laboratory Assessment of the Performance of Coarse Granular Materials for Pavement Foundation Design

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ABSTRACT: A performance based specification for road foundations potentially allows any material that can be assessed as 'fit for purpose' to be used, and encourages the wider use of marginal and recycled/secondary materials. For such a specification to be implemented information of material stiffness and resistance to permanent deformation is required for analytical design, and tests must be available to validate the design parameters onsite. Therefore a routine, economical laboratory-scale test needs to be developed to assess the performance and suitability of any potential foundation material to provide data for design, and ideally such a test should link to the field-based compliance testing. To facilitate this a large-scale laboratory test has been developed to assess the performance of coarse granular materials, typical of those used in UK pavement foundations. The test utilises a heavy duty steel box with a synthetic base layer, and portable test devices. This paper evaluates the performance of the test by comparing the results from a compacted sample of a typical site won "capping" material to associated field data. To validate the test methodology analysis of the stiffness test data for each layer compacted within the tests sample is presented. The effects of a soft and rigid base condition, and wetting and drying of the material is shown to have a significant effect on the measured values of both stiffness and strength. However, there appears a reasonable relationship between the laboratory results for the soft base condition and the field data.

KEY WORDS: Performance assessment, granular material, composite stiffness, dynamic plate test.

1. INTRODUCTION

A new UK performance-based specification for road foundations potentially allows the more efficient use of a wider range of construction materials . This paper describes the development of a large-scale laboratory test to assess coarse granular materials prior to their use on site.

The test aims to measure the engineering properties of capping materials in the laboratory at material selection stage, for assessment of their expected performance and acceptability for use in a road foundation. The test proposed is suitable for (coarse) granular capping and unbound marginal/recycled materials, it being sufficient in size to incorporate the full range of material particle sizes currently allowed in the UK (i.e. up to 125mm). Dynamic plate bearing tests are used to determine the elastic stiffness modulus, strength is assessed using the Dynamic Cone Penetrometer (DCP) and material compacted density is also assessed. From the test, the materials assessed can be deemed acceptable (i.e. a type approval), or provide indicators of expected performance in the field for incorporation in design.

Within the paper the tests currently available to assess the performance of granular materials (both in the field and in the laboratory) are briefly discussed. Following this the requirement for a tests to evaluate large particle size materials is described. The large-scale test apparatus developed, sample preparation and testing methodologies adopted are detailed. A recent programme of work assessing a the performance of a site-won sandy GRAVEL with the method is presented. Finally the outcome of the development of the apparatus is discussed, with its relative merits, limitations and recommendations for future work being considered.

2. BACKGROUND

In the UK a performance based specification for road foundations is being developed (Fleming et al., 2003). It requires the constructed road foundation to achieve a series of target performance related parameters. These include a target stiffness (measured by a dynamic plate test) and specified target density, with measurements made both on the formation and foundation surface. Additionally to limit permanent deformation it includes a limit on the permitted maximum surface rutting caused by construction traffic, (related to the foundation thickness provided to protect the subgrade from damage). In the UK road foundations are traditionally made from a good quality crushed rock 'sub-base' imported from a quarry, although if the subgrade is poor an improvement layer known as 'capping' may be used. This Capping should ideally, be local site-won material, and is used to help provide a better construction platform for the more tightly specified overlying sub-base. However if a wider range of new or recycled materials are to be allowed, a constructor will need some assurances of likely material performance before construction.

Therefore a routine, economical, laboratory-scale means of assessing the performance of potential pavement foundation materials is required if a greater range of foundation materials is to be allowed. Such a test will provide confidence that the proposed material meets the performance targets set in the specification, or confirm the data upon which the design is based. The laboratory approach helps material selection prior to evaluation in full scale field trials by narrowing down the number of materials that potentially may be suitable.

However, there are many challenges for attempting to replicate the site conditions in the laboratory, issues include allowable maximum material particle size, test boundary conditions, appropriate laboratory preparation and material compaction, test mould size, and measurement methods. For example substrate stiffness is known to both influence and limit (by a factor of three) the stiffness achieved by any overlying granular layers. Therefore the substrate used in the test will provide upper and lower bound limits to the measurable stiffness (Powell et al., 1984). Additionally, the influence of the weather on construction may influence the materials performance, due to changes in water content or due to its moisture susceptibility, and therefore these issues relative to any design or target values need to be assessed. It also has to be considered that pore water pressures can develop during compaction and reduce the stiffness of granular materials (Lekarp et al., 2000), these may then equalize with time, and the foundation stiffness increase. It also has to be considered that the methods used to evaluate the material properties are known to affect the data collected, therefore the same techniques used to measure the performance parameters in the field should perhaps be used in the laboratory to ensure compatibility between the data (Fleming et al., 2000)

2.1 Field Measurement techniques for Pavement Foundation Performance

There exist several in-situ stiffness measuring devices, such as the static plate bearing test and more contemporary portable dynamic plate test devices. The portable devices are considered more appropriate for commercial use as they are quicker and recreate more closely the dynamic nature of loading of a wheel. The portable devices typically measure a single deflection of the bearing plate (or the ground) under a transient load pulse, and the derived stiffness is termed a 'composite' stiffness (E_{comp}) as the measured deflection is a result of more than one layer of material (Fleming et al., 2000). The portable devices such as the Prima 100 can typically apply a stress of up to 150kPa over a period of approximately 20 milliseconds, via a 300mm diameter bearing plate. The pressure bulb depth (zone of influence) created as a result of the contact stress is equal to approximately 1.5 to 2 times the bearing plate diameter and so the composite stiffness measured is often a combination of the stiffness response of more than one material in a layered road foundation structure. A full review of such devices is presented by Fleming et al. (2002) and Rahimzadeh (2004).

The material's shear strength can be related to its resistance to permanent deformation (Frost, 2000). The in-situ strength of pavement foundation materials can be conveniently assessed indirectly using the Dynamic Cone Penetrometer (DCP). Problems can occur with the small cone and low impact energy in either very strong soils or those with very coarse particles (Fleming and Rogers, 1995). However, the DCP is a useful and simple-to-use portable tool for assessing changes in material strength.

The Clegg Impact Hammer is also a useful simple and portable tool used to assess and control the compaction of granular soils in the field (Kim et al., 2005). It measures the maximum deceleration of a 4.5kg mass 50mm diameter cylindrical hammer, falling through 450mm to impact the surface of the material under test. The Impact Value (IV) reflects changes in the near-surface strength of the compacted material and has traditionally been used in lieu of a direct density measuring device, to compare between materials prepared in the laboratory and field.

A direct method of material performance assessment is by a full-scale foundation trafficking trial. Sections can be trafficked to assess the design performance and material behaviour under actual vehicle loading conditions. Depth of rutting is then measured to indicate the resistance to permanent deformation directly. However, whilst this method may be advocated for larger schemes, design validation and material assessment, first in a laboratory test is desirable and efficient.

2.3 Laboratory Assessment of Performance

A number of laboratory tests already exist that can be used to assess the performance properties of granular materials. These element tests include the Triaxial Test, the K Mould and the recently developed Springbox (Edwards, 2004). However, in these tests the maximum particle size of suitable samples is generally restricted to 20mm, (or in the case of the Springbox, 40mm). For larger particle sizes the tests become very cumbersome and relatively complex (e.g. the large repeated load triaxial test and large K mould). For capping materials used in the UK a maximum allowable particle size of 40mm potentially excludes 25% of the sample (by mass) of a Class 6F1 capping and as much as 55% of a Class 6F2 capping (MCHW, 2004). In addition, the methodology of stiffness measurement in these tests makes direct comparison of results with field measurements (using the portable plate test devices) difficult. As a consequence, these element test methods are considered unsuitable to routinely assess the behaviour of large particle size coarse granular materials.

To assess very coarse aggregates it is considered necessary to use larger test moulds which contain a representative sample and reduce boundary influences on the sample it has been suggested that a 10 times the particle size should be used as a minimum (Lekarp et al 2000). A very large rigid box was used by Tingle and Jersey (2005) to evaluate cyclic plate load testing of geosynthetic-reinforced unbound aggregate roads. In their work a 4.5m^3 reinforced ‘containment vessel’ was used to provide a compacted substrate of (0.8m thick) and crushed limestone base course (0.36m thick), into which a sample could be compacted to replicate field conditions.

2.4 Test Philosophy and Requirements

From the above it can be seen that any test developed must aim to provide comparable performance measurements between the laboratory and the field, and be able to assess the performance parameters of stiffness and strength. A large test mould is deemed necessary to enable a representative sample of material with particle size up to 125mm, to be evaluated. The test mould should be rigid enough for the sample to be adequately compacted in layers to match field compaction. However, it must have appropriate boundary conditions to provide similar support to that expected in the field. The compactive effort used to compact samples should similar to that produced on site. Additionally an ability to simulate field water contents and drainage conditions is desirable. Finally the test developed has to ideally be practical, relatively simple, routine and must be able to be implemented effectively commercially.

Therefore, a large resiliently test mould into which materials can be compacted is proposed. Measurements of stiffness and strength should be made with the same devices that are suggested for performance evaluation in the field. This should provide an appropriate and representative test that meets most of the requirements detailed above..

3. APPARATUS AND TEST METHOD DEVELOPMENT

3.1 Test Apparatus

A large rigid steel mould of internal dimensions 1m x 1m x 0.5m deep was constructed, (Figure 1). It comprised controlled drainage points evenly spread about its base, to allow wetting and drying of the sample and to facilitate drainage.

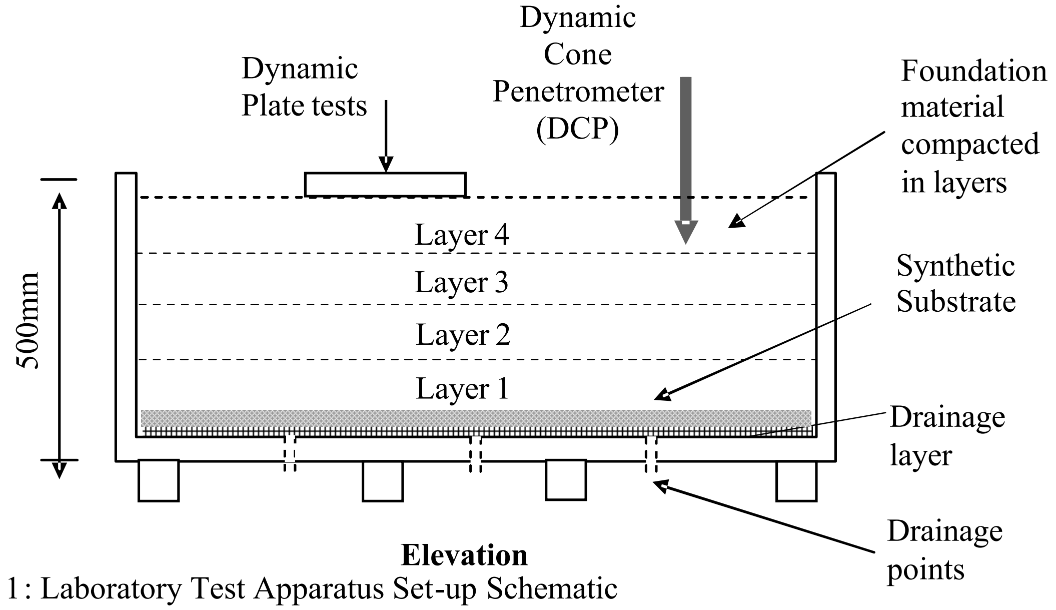

Figure 1: Laboratory Test Apparatus Set-up Schematic

A synthetic substrate layer was used within the mould to create a reduced base stiffness condition. The stiffness measured directly on this layer aimed to be similar to the stiffness of a typical UK subgrade. A synthetic rubber sheet, as used previously (Fleming and Rogers, 1994), of 0.95m x 0.95m by 20mm thick was placed in the based of the mould. The rubber had a surface hardness of between 40-50 IRHD0 with a density of 1.1kg/m^3. The rubber's composite stiffness was approximately 45MPa measured by a dynamic plate test.

A thin drainage layer was installed between the base of the mould and the synthetic substrate to facilitate drainage of the sample. A 5mm thick rigid plastic geo-drain fitted with geotextile filter on both sides was used.

3.2 Material Used

The material tested was classified as a sandy GRAVEL, with a natural water content ranging between 4-7%. The particle size distribution and compaction behaviour of several samples were assessed, and the sample predominantly fell within the 6F1 capping classification (MCHW, 2004). The material was sourced from a motorway site where it was being used as a site won capping. Field measurements on the motorway site where the capping was being used, found the subgrade to be a soft to firm clay. The field measured E_{comp} measured on the capping at this site after its compaction found for a 250mm thick capping a stiffness of 35MPa was obtained which increased to 112MPa for a 600mm thick capping.

3.3 laboratory Sample Preparation

The optimum water content for material tested was derived from a standard laboratory compaction test (BS 5835, 1980). A large capacity mixer was used to facilitate wetting or drying of samples to optimum water content prior to compaction. The material was installed in four layers of 100mm thickness. Compaction was performed using a 56kg electric vibrating rammer, with four passes for each layer, which accords with the standard UK specification for compaction (MCHW, 2004) and gave values of density in the rigid container measured using the sand replacement method similar to those obtained in the compaction test.

3.4 Stiffness and Strength Measurement

Once the material was compacted in the mould the order in which measurements were made with the various devices was important to minimise sample disturbance. The stiffness measurements were made before the intrusive strength readings. The composite stiffness (E_{comp}) was measured using the Prima dynamic plate test, at five positions around the surface of each layer as the layers were built up. One tests was located at the centre of the mould (Position 1), the other four test locations were placed at the corners of the mould with the centre of the bearing plate approximately 250mm from the mould side walls (positions 2 to 5). After completion of compaction of each layer, E_{comp} was measured at all five locations, a DCP measurement was also made at the centre point. Repeat E_{comp} test (and the DCP test) were made 24hours later to assess the effects of any pore water pressure equalisation prior to compaction of the next layer.

The Prima dynamic plate test was performed using a 300mm diameter plate with the geophone contacting the material surface. The device was positioned ensuring good surface contact and three pre-compaction drops at 100kPa were applied to seat the plate firmly. Three further drops were then applied, at 100kPa contact stress (as per the manufacturers proposed test protocol). The average stiffness from the latter three drops is used to express the composite stiffness. A 300mm diameter static plate test was performed on the final (i.e.

400mm) layer (BS 5930, 1999). The Clegg Impact Hammer test was performed on each layer with three tests at each of the five test locations.

3.5 Laboratory Tests Performed

To evaluate the material from the Motorway project and to assess the suitability of the test mould the following series of tests were performed. Initially different base boundary conditions were assessed, a test was performed where the sample was compacted directly onto the steel base of the mould, which provided a substrate (E_{comp}) stiffness of 200MPa. In the second test a synthetic rubber substrate was placed in the box to provide a lower substrate stiffness (E_{comp} 40MPa). The moisture susceptibility of the capping was assessed by saturating it through the surface of the compacted sample and allowing drainage through the base, (as might be expected during poor weather on site). The composite stiffness and strength were re-measured upon saturation and then again after a period of drainage, repeat cycles of wetting and drainage were also performed.

4. RESULTS AND DISCUSSION

4.1 Base Boundary Condition

The effects of the two base boundary condition caused significantly different performance of the material assessed. Figure 2, presents composite stiffness and layer number/thickness for the synthetic base condition. It shows a gradual increase in stiffness with layer thickness, as would be expected.

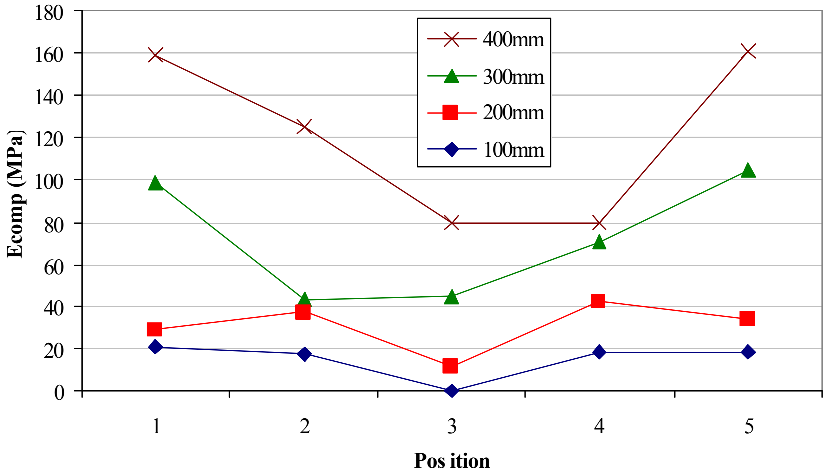

Figure 2: Composite stiffness for the sandy GRAVEL layers on synthetic substrate versus test position

For the very stiff substrate the relatively high stiffness of the base 'masked' the stiffness of the capping in the composite measurement – (i.e. the stiffness ratio of the two materials is too high) based on these results the use of a rigid mould base was rejected. The stiffness ratio between the capping and rubber is much less than the stiffness ratio between the capping and steel base and it is considered that the rubber base lining is more representative of field conditions. With the synthetic subgrade the ratio of E_{comp} top of capping to subgrade was approximately 3:1 (i.e. 120MPa versus 40MPa) which accords with Powell et al, (1984). The behaviour is also similar to that expected for a capping on a soft to firm clay subgrade and this was confirmed by similar data being measured in the field. However, it has to be considered that the elastic synthetic substrate may have affected the capping layer response during compaction. It is more difficult to ascertain these effects however, as the compacted material densities achieved were very similar between the two substrate conditions assessed. It is considered that more confinement could be afforded after compaction on the elastic base by allowing more particle reorientation during compaction, hence influencing behaviour.

4.2 Pore Water Pressure Equalisation

The effect of time after installation/compaction for the material to equilibrate and dissipate any excess pore water pressures was also investigated during these tests. It was clear that there was some effect of allowing the sample to 'rest' before assessment testing took place – and this observation was reinforced by some parallel test work in a Springbox (Edwards, 2004). The stiffness of the material increased by up to 2 times, 24 hours after compaction in the Springbox, and this observation is supported by field observed performance of compacted capping (Frost 2000).

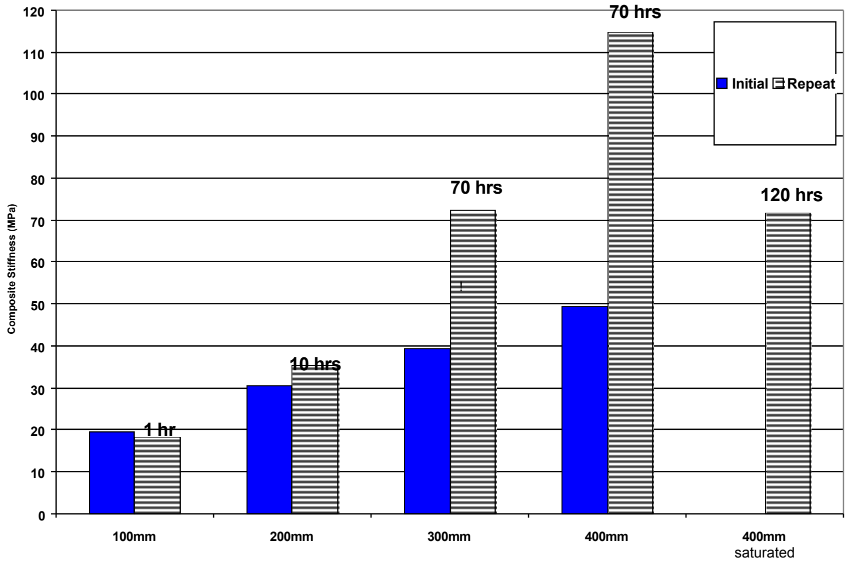

Figure 3: The effects of material rest after compaction on stiffness, sandy GRAVEL.

The repeat tests shown in Figure 3 are for several hours after layer installation, and show a substantial increase in composite stiffness after rest. However this may have been affected by surface drying during this period (this is further discussed below).

4.3 Wetting and Draining Effect

The effects of wetting to saturate the compacted materials followed by subsequent draining were investigated. In general a similar pattern of stiffness changes was observed for both base conditions and the sandy GRAVEL material was clearly moisture susceptible, (Figure 4, synthetic substrate condition). The stiffness data variability across the test box is presented as a Coefficient of Variance (CoV the ratio of Standard Deviation to the mean of the stiffness measurements, expressed as a percentage). The CoV shows significant scatter, especially early on during installation and during the wetting phases. However, the CoV reduces during drying and in general was approximately 20%, the range of measured stiffness appeared sensible, although slightly high compared to previous field measurements on a similar for capping (Fleming et al., 2000).

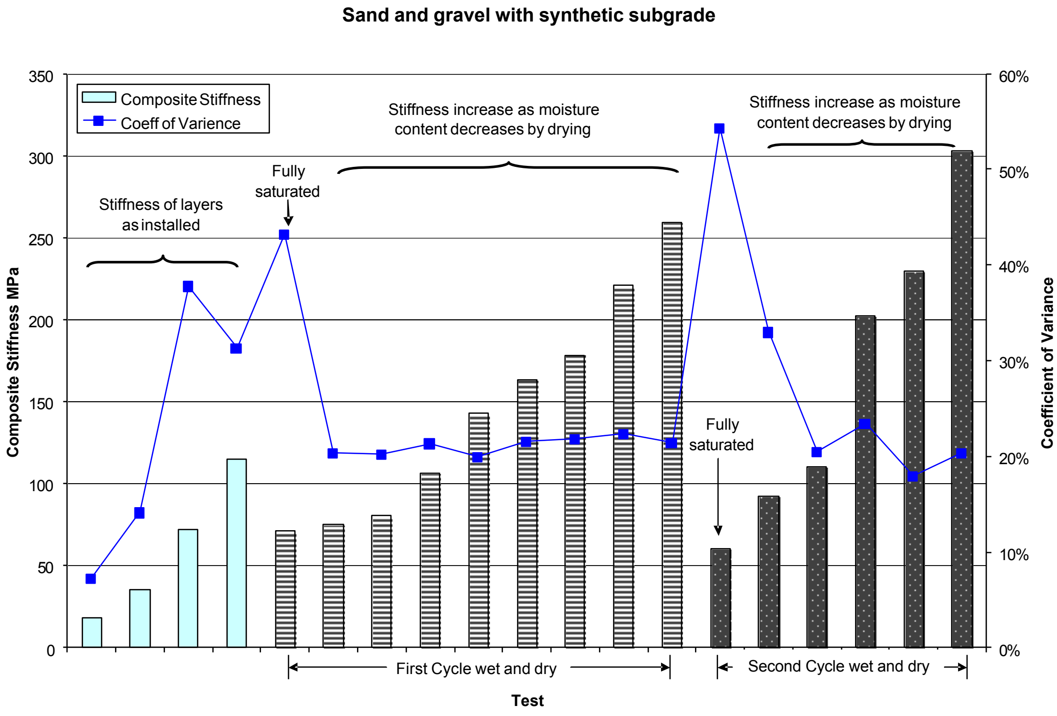

Figure 4: A summary of composite stiffness for the sandy GRAVEL on synthetic substrate.

The water content profile for the layers of the 'as installed' material and after the second cycle of draining (whereby the material could be excavated and the water content assessed) is presented in Figure 5. Figure 5 clearly shows that during the draining phase the sample dries preferentially from the top, and hence that the greatest suctions are indirectly observed here. In the laboratory the samples were open to drying effect as well as draining. Contrasting the two base conditions during draining, shows that the initial water content profiles during installation were similar, but that drying ambient conditions (i.e. temperature and humidity) in the laboratory have dried each sample differently.

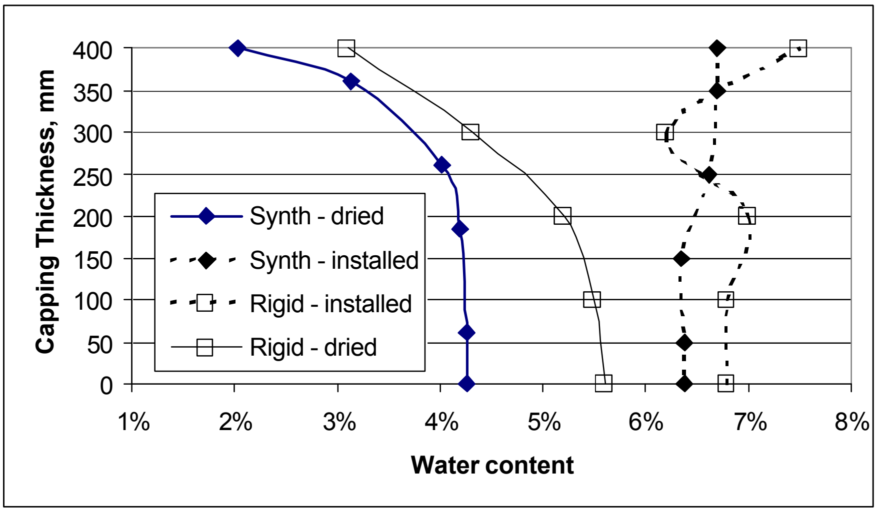

Figure 5: Water content profiles for the 'Rigid' and 'Synthetic' base conditions

Figures 4 and 5 combined demonstrate the high sensitivity of the capping material to the wetting and drying. This is an important issue for the field, for both measuring and achieving the performance targets. The performance measured on site should perhaps only be considered a ‘snapshot’ relating to the pore water pressures in the material at the time of testing.

The DCP data gave inferred CBR values of around 35-50% after placement. The DCP data suggested this material should be suitable for trafficking with regard to internal shear strength. In a wet state the CBR remained at around 50%, increasing to 300% after draining suggesting some aggregation and agglomeration of the materials.

5. CONCLUSIONS

A routine large-scale laboratory test for the assessment of coarse granular capping materials has been developed and some test data presented. The following conclusions are drawn from this work.

- It is considered routinely difficult to assess the expected field behaviour of aggregates with coarse particles in conventional tests in the laboratory, therefore there is a need for a large-scale test method which can accommodate such large particle sizes.
- The large-scale test developed can utilise the same equipment as is used in the field for direct comparison of composite stiffness and (indirect) strength data.
- The effect of a ‘rest’ period after installation was shown to have a large effect on the measured composite stiffness.
- The ‘soft’ base boundary condition effected by a rubber sheet was effective for compaction of the granular material assessed and was more representative of the field condition than the ‘rigid’ base condition.
- The sandy GRAVEL tested was found to be moisture susceptible and able to sustain negative pore water pressures that had a large effect on both its stiffness and strength behaviour.
- The changes in water content have important consequences for achieving site target values in a performance specification.

6. FUTURE WORK

This research at Loughborough University is now focused on providing more data sets and field work to validate the test method and expand the range of materials evaluated. The effects of pore water pressure and stress dependency are to be further assessed. Variations of synthetic substrate stiffness will be evaluated to provide a better indicator of the likely range of composite stiffness of capping that may be achieved in the field.

7. ACKNOWLEDGEMENTS

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