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Characterisation of the mechanical behaviour of layered clay sedimented using a geotechnical centrifuge

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ABSTRACT: Ritchie (2023) describes how Speswhite Kaolin and Polwhite E Kaolin can be combined at very high water contents to create a slurry from which a series of layers of clay can be sedimented in a soil container using a geotechnical centrifuge. Because Polwhite E Kaolin has a larger particle size than Speswhite Kaolin the Polwhite E Kaolin sediments first, creating a higher permeability deposit at the base of each sedimented layer. This bed of sedimented layers of clay can then be consolidated in a consolidation press to reach states allowing the construction of a reduced scale physical model of, for example a tunnel excavation, which can be tested in the centrifuge. The paper presents results of preliminary triaxial tests characterising the strength and volumetric compression of this laboratory sedimented clay. In addition, these data are compared to data from specimens of clay where the Speswhite Kaolin and Polwhite E Kaolin have been mixed evenly or reconstituted at water contents of approximately 120%, allowing the effect of the sedimented structure to be quantified with respect to an equivalent reconstituted soil as is frequently undertaken when studying natural sedimented clays. The preliminary data presented indicates that the sedimented clay has a stable structure or fabric which only affects the specific volume or packing of the soil grains at a given value of mean effective stress. The sensitivity of the sedimented clay when compared to the same clay reconstituted is as much as 4.7. The angle of friction or coefficient of friction of the sedimented clay appears to be very similar to that of the reconstituted clay.

KEYWORDS: Triaxial, sediment, structure, centrifuge

1 INTRODUCTION

Many naturally occurring clays have been deposited by sedimentation. These sedimentary clays have a layered structure that affects their mechanical behaviour and their permeability. Stallebrass *et al.* (2007) found that it was possible to recreate this sedimented structure in the laboratory if a slurry of reconstituted London Clay, water content 5800%, was sedimented in a long tube through saltwater. The resulting samples had a layered structure with segregation of the larger particle sizes and layering in the finer particles. This structure or fabric was stable and could be characterised by a sensitivity, S_t , as defined by Cotecchia & Chandler (2000) of between 1.5 and 1.8.

Ritchie (2023) developed techniques to create sedimented clay soil beds in centrifuge models to be able to investigate the effect of this sedimented fabric on the deformation of soil structures, and particularly the long-term response of these structures during consolidation. The latter has been found to be critically dependent on the anisotropy of the permeability of the surrounding soil for example by Wongsaroj *et al.* (2007). The layering in sedimented soils leads to anisotropic permeability, with the horizontal permeability significantly higher than the vertical permeability. Following an extensive study, Ritchie (2023) developed a methodology that enabled sedimented layered samples to be created in a geotechnical centrifuge using slurries with a water content of around 500%. These slurries contained a combination of 70% Speswhite Kaolin and 30% Polwhite E Kaolin and a dispersant such as sodium hexametaphosphate. The sedimented beds of clay could then be carefully consolidated in a consolidation press to provide a layered bed of clay that could be used for physical model making. The sample preparation method by Ritchie (2023) was repeatable and used to prepare beds of clay for the tests reported in this paper. Beds of clay sedimented in this way show a ratio of horizontal to vertical permeability of $17 \times 10^{-9} \text{m/s}$ to $4.6 \times 10^{-9} \text{m/s}$ or 3.7:1.

The aim of the triaxial tests reported here was to examine the differences in volumetric and deviatoric response of specimens obtained from the sedimented beds of clay and

specimens obtained from reconstituting soil from these layered beds of clay. This is an approach followed by many researchers, for example Cotecchia & Chandler (2000), Amorosi & Rampello (2007) and Gasparre *et al.*, (2007). It should enable the sensitivity, S_t , of the sedimented clay to be determined and separate state boundary surfaces for the reconstituted and sedimented clay to be plotted. A preliminary programme of four triaxial tests have been undertaken involving isotropic consolidation and undrained shearing from normally compressed states.

To determine the effect of the sedimented fabric and quantities such as sensitivity, it is necessary to have an accurate measure of the water content and hence specific volume of the clay. As will be shown below, the water content varies throughout the beds of sedimented clay and in the triaxial specimens obtained from them, consequently it was important to measure the variation in water content in the specimens and decide on a means of obtaining a representative average water content for the specimen. This effect is particularly pronounced in these sedimented samples because the layers are relatively thick.

2 METHODOLOGY

2.1 Clay soils sedimented and tested

The clay bed sedimented was made up of Speswhite kaolin and Polwhite E kaolin, both supplied by Imerys Ltd in powder form and combined with distilled water and sodium hexametaphosphate. The sodium hexametaphosphate acted as a dispersant to minimise the slurry water content from which the clay was sedimented. Polwhite E kaolin is a medium particle size kaolin, with a distribution such that a maximum of 35% of the particles are larger than $10 \mu\text{m}$, and a minimum of 25% are smaller than $2 \mu\text{m}$. Speswhite kaolin is a very fine particle size kaolin with approximately 80% of particles smaller than $2 \mu\text{m}$. These particle size distributions are as specified by the manufacturer. Ritchie (2023) notes that sodium hexametaphosphate is a dispersant used to prepare kaolinite clay suspensions for the ceramic industry. As Imerys Speswhite

kaolin clay and Polwhite E kaolin clay products are also sold to the ceramic industry and designed for dispersion, this was considered a good choice to reduce the water content of the slurry required to obtain a sedimented structure. The clay slurries used for the sedimentation comprised 30% Polwhite E kaolin, 70% Speswhite kaolin and 0.05% sodium hexametaphosphate by weight with a water content of approximately 500%.

2.2 Preparation of sedimented clay bed

The sedimented clay bed was only used for these element tests and consequently only three layers were sedimented. Each layer was made up of approximately 30 litres of slurry. The slurry was mixed in a Metcalfe Planetary mixer and then placed in a centrifuge soil container (strong box) with the dimensions 550 mm wide by 200 mm deep by 350 mm high. At the base of the strongbox there was a porous plastic sheet above a herringbone pattern drain machined into the base. Above the porous plastic was a filter paper held in place by an aluminium frame so that it did not float. Once the slurry was placed in the strong box the centrifuge was accelerated to 100g and left for an hour for sedimentation to take place. After the centrifuge was stopped, most of the displaced water above the sedimented layer was siphoned off and another layer of slurry was added. This process was repeated once more to sediment the third and final layer. On this occasion the final layer contained slightly less slurry as it was not possible to fit all 30 litres into the strong box, which would normally have had an extension fitted. Following the sedimentation of the final layer, the strongbox was removed from the centrifuge and placed in a consolidation press. The clay bed was then compressed to a vertical effective stress of 175 kN/m².

Figure 1 shows a picture of the sedimented clay bed once the strong box had been removed from the consolidation press.

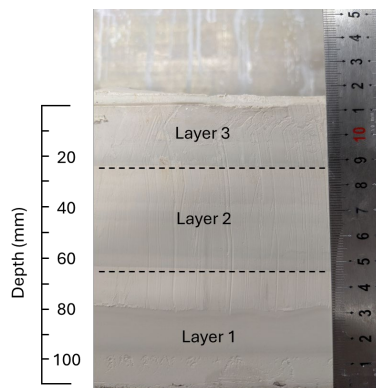


Figure 1. Annotated section of layered bed of clay in the centrifuge strong box adjacent to a steel rule.

2.3 Preparation of sedimented and reconstituted triaxial specimens

The sedimented triaxial specimens were obtained by pushing thin-walled tubes vertically into the clay bed from the surface to the base of the bed and then excavating to allow the specimen to be extracted horizontally. The thin-walled tubes had a nominal internal diameter of 38 mm. These tubes were then carefully extruded into a cradle, and specimens were trimmed to length. The lengths of the trimmed sections were measured so it was possible to match the specimen obtained to its location in the clay bed shown in Figure 1. The specimen was then placed in a stress path triaxial apparatus being used as a conventional triaxial apparatus. A typical specimen extruded and placed in a cradle before trimming to length is shown in Figure 2.



Figure 2. Sedimented clay specimen

The reconstituted specimens were obtained by taking a vertical section of the clay bed shown in Figure 1, cutting it into small lumps and mixing it at a water content of approximately 120% with distilled water to form a slurry which was then consolidated in 38 mm diameter PMMA floating ring consolidation tubes to a vertical effective stress of 62 kN/m². These specimens were then trimmed and extruded directly into the cell.

2.4 Triaxial testing

Four specimens were tested; Two sedimented and two reconstituted. In all tests the specimens were subjected to one step isotropic consolidation to one or more mean effective stresses and then sheared undrained from a normally compressed state to an axial strain of approximately 12%, which was before noticeable discontinuities were apparent in the specimen. Table 1 gives the mean effective stresses to which each specimen was consolidated. The offcuts from specimens were used to obtain initial water contents for the specimens but it is acknowledged that these were unlikely to be very representative of the water content of the layered specimens. The final water content of the whole specimen was also measured by dividing the specimen horizontally into five sections and measuring the water content of each section.

Table 1. Triaxial tests undertaken

Test	Stress after one step consolidation (kN/m ²)			Comment
	Stage 1	Stage 2	Stage 2	
S1	100	200		Sedimented
S2	300	400		Sedimented
R1	100	250	400	Reconstituted
R2	200			Reconstituted

3 RESULTS

3.1 Water content measurements

Before obtaining the specimens from the sedimented clay layer, a thin-walled tube was used to obtain a core through the sample which was extruded and divided horizontally into sections of between 8 and 13 mm in length. Water contents were obtained for each section and are plotted in Figure 3 adjacent to an image of the layered bed of clay. In the plot the water content measured is shown as the average water content for that section and hence the plot is stepped. In the clay the variation in water content is likely to be smoother and the true variation in water content, measured as between 57.8 and 44.0 % could be more extreme.

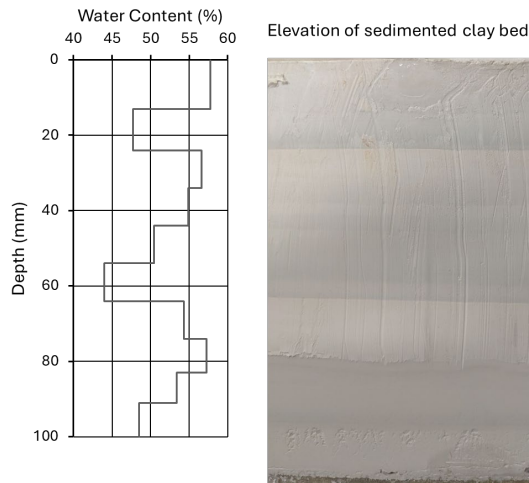


Figure 3. Water content of sections of sedimented clay bed

The upper parts of the layers, predominantly comprising Speswhite Kaolin, have higher water contents. The lower parts where there is Polwhite E kaolin have lower water contents. The specific volume of the specimen will be calculated from an average water content for the specimen as would occur were a naturally sedimented clay tested. To evaluate what might be the best method of deriving this average water content four methods have been compared.

Table 4 gives initial water contents measured from; (1) offcuts, (2) weighted averages computed by matching the location of the specimen to the original sedimented clay bed, (3) weighted averages computed from the average final water contents and (4) weighted averages computed from the average final water content ignoring the section of the sample nearest the base pedestal. The latter was considered because at the end of the test when the specimen is unloaded to remove it from the cell, water in the porous stone is likely to be drawn into the base of the specimen causing a local increase in water content that may not be representative of the overall water content in the sample. However, for tests R1 and R2 the difference between the initial water contents calculated from the final water content with (3) or without (4) the end section is not significant and consequently, water content (3) will be used to calculate specific volumes as it represents the water content of the whole sample tested. Specific volumes calculated using the initial water content (2) computed from the clay bed values will also be plotted to indicate the possible variability in the volumetric states of the sedimented soils. Water content (1) for the reconstituted specimen used in test R1 is rather low because all the trimmed soil was used and, at the ends, this may have had a significantly lower water content.

Table 2. Water contents

Test	w/c (1)	w/c (2)	w/c (3)	w/c (4)
S1	0.513	0.522	0.538	0.523
S2	0.501	0.523	0.531	0.513
R1	0.478	-	0.506	0.504
R2	0.487	-	0.482	0.479

Figure 4 gives the variation in final water content for the four samples tested showing, as noted above, that there is only a small increase in water content in the lower section of reconstituted samples of 0.5%. For the sedimented samples the lower section has the highest water content, but water contents are generally more variable. For test S1 the final water content varies by 11.7% and for test S2 by 10.1%, whereas for tests R1 and R2 the variations are 1.5 and 2.7% respectively. The variations in the final water contents for the sedimented samples are comparable to the variation in water content with depth in the sedimented clay bed which was 13.8%.

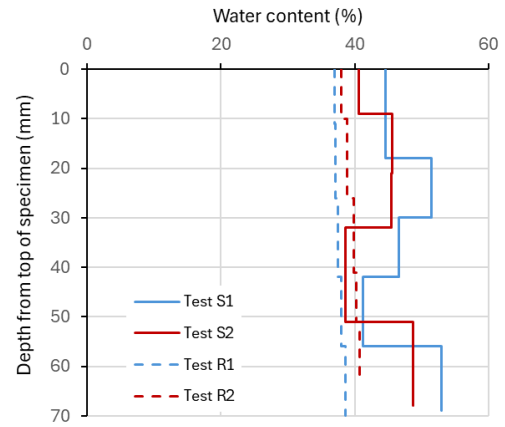


Figure 4. Final water contents.

As noted above considerable effort has been made to find a consistent measure of the water content of the sedimented specimens because this will determine the volumetric response and the value of sensitivity, S_t , measured for the soil.

3.2 Volumetric compression

Figure 5 shows the end points of the one step isotropic normal compression stages plotted as specific volume against the natural logarithm of the mean effective stress for all four tests. For tests S1 and S2 specific volumes have been calculated using the final measured water content and the initial water content inferred by matching the sample tested to the water contents measured in the sedimented clay bed. The latter points are the open symbols on the graph. For tests R1 and R2 specific volumes have been calculated using the final measured water content.

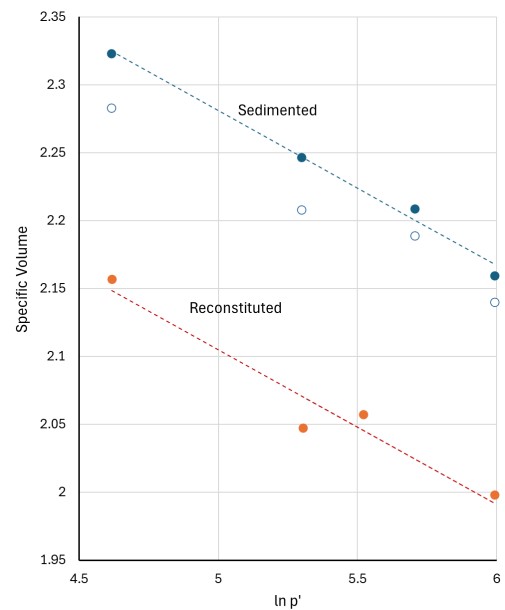


Figure 5. Graph of specific volume versus $\ln p'$ at the end of one step consolidation stages for all tests.

Two distinct lines have been added to the graph representing the isotropic normal compression lines for the sedimented and reconstituted clay. Both lines have gradients fixed to be consistent with a value of λ of 0.114, where λ is defined using the equation:

$$v = N - \lambda \ln p' \quad (1)$$

This value of λ has been used because it is the average of the values obtained from best fit lines to the data where specific volume has been calculated from the final water contents, (3) in Table 2. The gradients of the best fit lines varied by 0.002 and so using a consistent value seems reasonable. For the lines shown in Figure 5, N for the reconstituted soil is 2.675 and N for the sedimented soil is 2.851. Because it is reasonable to assume that the lines are essentially parallel, it appears that the sedimented structure created in the clay bed in the centrifuge is stable. If, as defined by Cotecchia & Chandler (2000), sensitivity, S_i , is the ratio of the mean effective stresses at any constant value of specific volume, then for the values of N and λ given above the sensitivity of the soil could be as high as 4.7. This is greater than the sensitivity of 2 reported by Ritchie (2023) when comparing sedimented and reconstituted Polwhite E kaolin and sedimented and reconstituted Speswhite Kaolin. The open symbols give an indication of the variability in the values of specific volume used which could reduce the sensitivity to around 3.3.

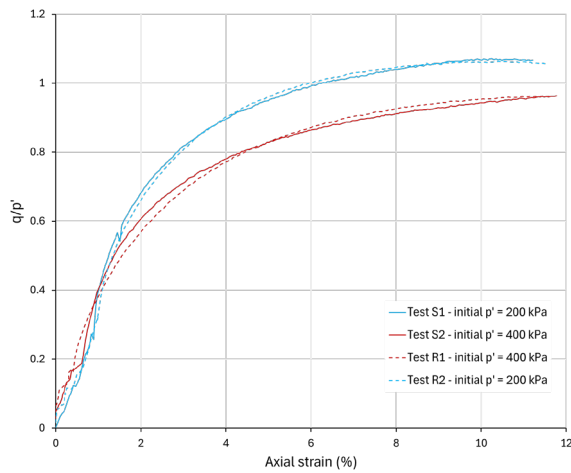


Figure 6. q/p' change with axial strain during shear loading

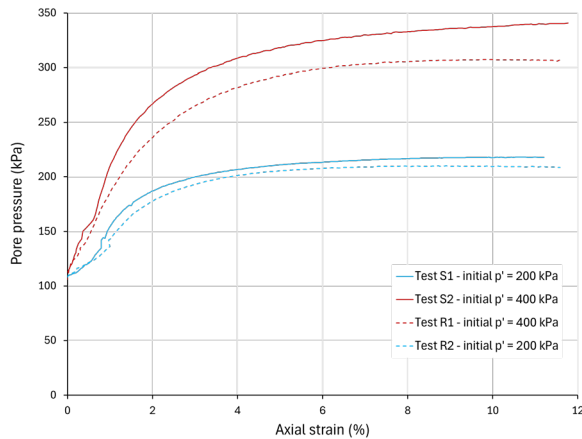


Figure 7. Pore pressure change with axial strain during shear loading

3.3 Undrained shear loading to failure

At the end of each consolidation stage the specimens in all tests were loaded undrained under strain control. The stress strain data from these tests is plotted as stress ratio, q/p' , against axial strain in Figure 6. Figure 6 shows that the normalised stress/strain response of the sedimented and reconstituted samples sheared from the same mean effective stress is very similar. In Figure 7 the corresponding pore pressure response during shearing indicates that none of the soil specimens

reached a critical state, although the tests on reconstituted samples R1 and R2 are closer to a constant value of pore pressure at the end of the tests. The tests are all terminated at approximately 11.5% to ensure they are not affected by the development of shear planes and localisation of deformation along these planes. This localisation leads to a decrease in the apparent deviator stress as the specimen is no longer behaving as a continuum.

Figure 8 shows stress paths in deviator stress, q' , versus mean effective stress, p' , space. The reconstituted samples reach higher deviator stresses, particularly when tested at the higher initial mean effective stress. A possible critical state line has been drawn representing, $M = 1.0$, which is an average value for the end points of the curves plotted and in addition a critical state line representing M for Speswhite Kaolin which is 0.89 (for example Lalicata et al. (2023)).

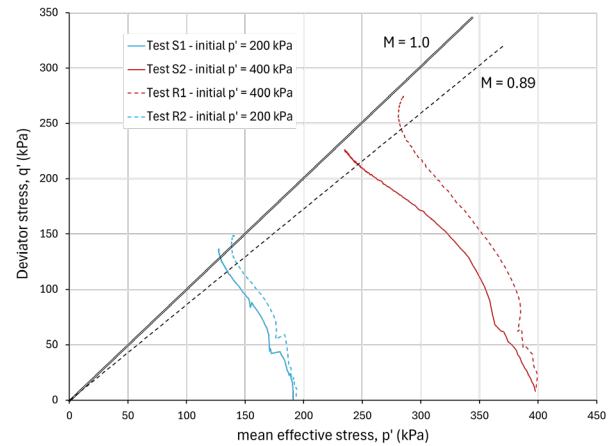


Figure 8. Effective stress paths for undrained shear loading.

The 30% Polwhite E Kaolin with a larger percentage of particles in the fine silt range has increased the critical state coefficient M and hence the critical state angle of friction of both the layered and reconstituted soils. Further testing would be needed to establish the angle of friction more precisely. A slight misalignment of the specimen and load cell in all tests has affected the behaviour observed at deviator stresses up to approximately 50 kN/m², but this should not have affected the final states of the specimens.

3.4 Volumetric states during shear loading

The specific volume and mean effective stress corresponding to the end states in Figure 8 have been added to the isotropic normal compression data for the four tests initially presented in Figure 5. These data are the square symbols in the graph. Lines of best fit at the same gradient as the normal compression lines have been plotted through these data to represent possible locations of critical state lines in $v:\ln p'$ space. The line representing a possible critical state line for the sedimented soil is more convincing than that for the reconstituted soil which is affected by a significant variation in water content of the soil in Test R2.

In Figure 10, data from Figure 8 are normalised by the equivalent pressure on the normal compression line of the reconstituted soil. Where the equivalent pressure is defined as

$$p'_e = \exp\left(\frac{N - v}{\lambda}\right) \quad (2)$$

Where v is the current specific volume and N and λ are equal to 2.675 and 0.114 respectively as defined in section 3.2 for the isotropic normal compression line of the reconstituted soil.

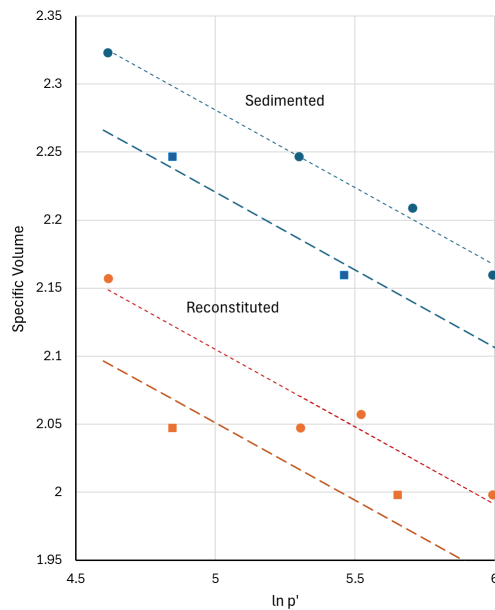


Figure 9. End states of undrained shear tests to failure.

When normalised in this way the reconstituted and sedimented soils clearly sit in two groups representing the approximate locations of two normalised state boundary surfaces. Inconsistencies in the water content measurements mean that neither the reconstituted nor the sedimented normalised stress paths clearly define a unique state boundary surface. However, these are preliminary tests and only two tests have been carried out in each case.

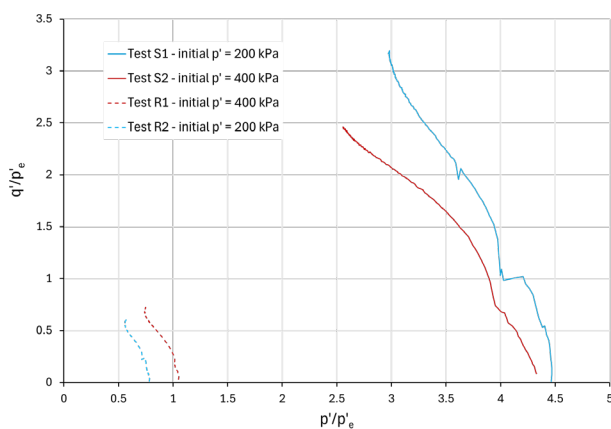


Figure 10. Normalised stress paths

4 DISCUSSION OF RESULTS

A set of four preliminary triaxial tests have been undertaken. Two tests were on specimens sampled from a sedimented clay bed created in the geotechnical centrifuge a City St Georges, University of London and two were from specimens prepared by reconstituting soil taken from the same bed of sedimented clay. A significant variation in water content with depth was observed in the normally compressed sedimented clay bed which appeared to correspond to a difference between the water content at the top and bottom of the layers. This was also observed by Ritchie (2023) in oedometer tests on sedimented material. This difference in water content in the layers was maintained to some extent during the compression and shearing of the sedimented specimens in the triaxial tests. The reduction in this difference was probably just a consequence of the overall

reduction in water content of the samples during isotropic compression.

Using a weighted average water content taken from the end of the tests it was possible to find the isotropic normal compression lines for the sedimented and reconstituted samples. It should be noted however, that variations in the water content in the sample could lead to errors in the specific volumes plotted and consequently data were also plotted for the sedimented specimens using the weighted average water content from the start of the tests. This provides a measure of the possible error and the effect that error might have on the location of the normal compression line. The isotropic normal compression lines plotted are consistent with the sedimented clay having a stable structure or fabric as observed in natural sedimented clays such as London Clay (Gasparre et al., 2007) or Vallericca Clay (Amorosi & Rampello, 2007). However, the sensitivity, S_t of the sedimented clay is relatively high, 4.7 compared to values around 2 and 2.4 for London Clay and Vallericca Clay. London clay sedimented in the laboratory by Stallebrass et al., (2007) had a sensitivity of 1.8 - 1.5.

The undrained shear response of the sedimented clay sheared from a normally compressed state is very similar to the response of a reconstituted clay specimen sheared from the same mean effective stress. The focus of these tests was to assess the critical state of the clays and consequently no measurements of the clay stiffness are provided. The tests at different initial states tend to an average value of critical state coefficient, M , equal to 1.0. This is higher than the value expected for Speswhite Kaolin ($M = 0.89$) and must be a consequence of the addition of the coarser grained Polwhite E Kaolin. It appears that a ratio of 30% to 70% ensures that the angle of friction increases in both the reconstituted and sedimented samples and that the failure of the sedimented samples must have been along planes through both Polwhite E and Speswhite kaolin layers.

Critical states in terms of specific volumes and mean effective stresses have also been plotted and for the sedimented clay specimens appear to be consistent with a critical state line parallel to the normal compression line. Normalising the stress path data by the equivalent pressure on the reconstituted normal compression line for the clay allows regions where two state boundary surfaces might exist to be identified. These are quite separate and the normalised stress paths have similar shapes. However, the data is very sparse and Test R2 is affected by a possible error in water content measurement, so further testing is necessary and at a wider variety of states to determine the state boundary surfaces more precisely.

5 CONCLUSIONS

A method has been developed that allows layered sedimented clay beds to be created using a geotechnical centrifuge in a soil container, such that the clay bed can subsequently be used to model soil structures such as tunnels, foundations or deep excavations in these layered soils that have different horizontal and vertical permeabilities and a sedimented structure or fabric.

Preliminary triaxial testing has been undertaken to evaluate the sedimented fabric of these clay beds and how it affects the compression behaviour and critical states reached by the sedimented clay bed compared to clay reconstituted from the same clay bed. These preliminary results indicate that the sedimented clay bed has a higher sensitivity than many natural sedimented clays but that the fabric or structure creating this sensitivity is stable both during isotropic compression and undrained shear loading to failure. Because the layers created in the clay bed are large relative to the height of the specimens tested and there is a very significant variation in water content

from the top to the base of a layer, efforts have been made to obtain representative average water contents for the specimens by dividing the specimens into horizontal segments. Further work is necessary to enhance the measurement of water content to provide confidence in the calculations of sensitivity and the location of state boundary surfaces.

Ultimately, a good understanding of the mechanical behaviour of these clay beds sedimented in a geotechnical centrifuge is critical to interpreting centrifuge model tests using these clay beds, particularly if finite element analyses with constitutive models simulating this behaviour are used.

6 ACKNOWLEDGEMENTS

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