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Estimation of Shrink / Swell Potential and Variability of Clays by Small-Scale Suction Tests

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ABSTRACT The relationship between suction and water content gives crucial information about a soil. Small projects like economic housing do not warrant the time and cost of determining the full soil water suction curve. A considerable range of soil suctions can easily be achieved within a reasonably short time by using small samples, simple suction control and a high precision balance. It appears that in this way it may be possible to estimate heave potential and variability of soil properties at reasonable cost in an acceptable time. Variability assessment appears to be of great value and may offer significant potential for improving the reliability of foundation design on shrink/swell soils.

Keywords: Soil suction, Expansive clay, Shrink/swell, Heave potential, Soil variability.

1. INTRODUCTION

The tests presented here are part of an attempt to address problems with the current commercial methods for foundation indicator tests prevalent in Africa and also in other parts of the world. Such tests often involve procedures primarily intended for road construction materials and they frequently give poor estimates of volume change potential for undisturbed, in-situ, high clay-content soils. This is not very satisfactory since shrink/swell is the most frequent cause of damage to housing and infrastructure in many countries. Considerations of economy point to a need for simple tests with minimum skilled labour content, minimum sample preparation, very little opportunity for short-cuts and straightforward interpretation of results. Tests should relate directly to expansive potential, rather than general soil properties. Suction potential gives an indication of how readily a soil can draw in water. Change in water content is the cause of volume change. Suction potential should therefore be a good indicator of swell potential.

Variability in soil properties is another potential source of problems not only in design for expansive soils, but for many kinds of soils analysis. Little attention is drawn to it in many well-known soil mechanics text books. “Craig’s Soil Mechanics” (Knappet & Craig 2012) mentions variability in three places, Das makes no mention of variability in either “Principles of Geotechnical Engineering” (Das 2006) or “Advanced Soil Mechanics” (Das 2008). Fredlund and Rehardjo mention it once in “Soil Mechanics for Unsaturated Soils” (Fredlundand and Rehardjo 1993) and once in “Unsaturated Soil Mechanics in Engineering Practice” (Fredlund et al. 2012). Blight’s “Unsaturated Soil Mechanics in Geotechnical Practice” (Blight 2012) is one of few geotechnical text books which not only stress the existence of variability but also point out the dangers of ignoring it. “Reliability-Based Design in Geotechnical Engineering” (Phoon 2008) is dedicated to dealing with variability in several aspects of soil mechanics and merits widespread attention.

2. INDICATION OF SHRINK/SWELL POTENTIAL

Kassa (2005) found that Atterberg limits are not a reliable indicator of volume change under load. Sridharan and Prakash (2000) found that Atterberg limits can sometimes indicate expansive potential significantly higher or significantly lower than reality. Atterberg limits remain, however, the most popular indicators of shrink/swell potential. The linear shrinkage test, performed on raw soil samples allowed to air-dry slowly, gives a graphic indication of the extent to which a soil may change volume with water content. This gives a clear and reliable indication of how much a soil may shrink or swell under zero loading, but it does not indicate the likely forces (or pressures) which can be exerted in this change of volume and therefore the shrink/swell potential under load.

Clays expand when they draw in water. The force which can be exerted in this expansion depends on the strength with which they can suck in water. The suction of clays has long been recognized as a cardinal indicator of heave potential, but it is one of the least convenient indicators to measure. The plot of suction from saturation to desiccation is known as the soil water characteristic curve (SWCC). The SWCC is regarded as an indispensable part of a full unsaturated analysis (Fredlund et al. 2012), but it requires much time, skill and expense to measure.

3. RECENT ADVANCES AND CURRENT PRACTICE IN SUCTION MEASUREMENT

Three papers presented at the International conference on Soil Mechanics and Geotechnical Engineering in Paris 2013 deal with advances in techniques of suction measurement. Two other papers deal with measuring suction in practical engineering projects.

Advances in dew-point potentiometer technology should lead to extension of the range of suctions measurable by this type of instrument (Macek et al. 2013). The use of micro-porous membranes may allow quicker suction measurement in the 0-30 kPa suction range (Nishimura 2013). The use of a centrifuge may speed up measurement in the 0 to 900 kPa range (Reis et al. 2013). Such advances should hopefully lead to quick, convenient and economic assessment of the full range of soil suctions in the future. But in practical use, for assessing lime treatment on London Clay (Mavroulidou et al. 2013) and for modeling the impact of climate changes on embankments and cuttings (Mendes and Toll 2013), Whatman No.42 filter paper remains the method of choice. This time-honoured system takes typically two to six weeks for a suction measurement and requires careful laboratory technique (Bulut et al. 2001).

4. SMALL SCALE SUCTION POTENTIAL MEASUREMENT

A more limited indication of suction potential can be found by allowing samples to reach equilibrium at known temperature and humidity. Soil samples can be brought to equilibrium over saturated solutions of various salts (Blight 2013). Blight’s tests took typically 90 days. Although his equipment was cheap and unsophisticated, and the skilled labour component not large, the time frame is not feasible for normal engineering practice. In this paper the authors introduce modifications to Blight’s procedure which give quicker results, making enquiry into some important questions feasible.

This procedure involves using small pieces broken from a soil specimen. Breakage in high clay-content soils usually occurs along planes of existing weakness; the micro-structure and fabric of the soil are not greatly disturbed (See Figure 7). Samples are placed in small glass weighing bottles with ground-in lids. When closed, little air or water vapour leaves or enters in the time taken for weighing. Samples are weighed on an analytical balance and then placed with lids open in a container at controlled temperature and humidity (see Figure 1). Equilibrium moisture content is a measure of the suction potential of the soil under those conditions. Samples can be weighed periodically by closing the ground-glass lids and removing them from the controlled atmosphere to the analytical balance. For many of the tests performed in this investigation suctions corresponding to saturated solutions of KCl and NaCl were used, though both higher and lower suctions were also employed (as for example in generating the SWCCs shown in Figure 22). A climate chamber was used for many of the tests, often at settings which give the same suctions as KCl and NaCl. A climate chamber has the advantage of convenient control over a wide range of suctions and quicker equilibration due to active circulation. A description and flow-diagram of a streamlined procedure suitable for routine testing is detailed in section 10.

Figure 1
Above: samples in climate chamber. Temperature and humidity can be controlled to give a wide range of suction.
Below: samples in a readily obtainable storage container whose lid is air-tight.ample bottles stand on a perforated platform above a solution whose vapour pressure is known at various temperatures.

Figure 2 shows curves of moisture content against time at constant suction for samples of 30 clayey soils from a housing development in central South Africa. These 30 samples cover a very wide range of shrink/swell potential. The masses of the samples range between 25g and 35g. Starting water contents were as found in the sample bags and would probably be close to natural field values in most cases. The equilibrium moisture contents at 22MPa suction (corresponding to a saturated solution of KCl at 20^0C) vary from 3.6% to 12.6%. Correspondence between moisture retention and heave potential appears to be supported by the fact that the highest water retention samples have Plasticity Index (PI) in the region of 40, which would normally be considered an indication of high expansive potential. Those with the lowest water retention have PI below 15, which would normally be considered an indication of low expansive potential. More detailed tests have shown high coefficient of variability for many clayey soils, as can be seen in Figures 17 and 18 and also Figures 19, 20 and 21. Comparisons of expansive potential are therefore only loosely indicated by single tests. Multiple duplicate testing is needed for worthwhile comparisons of shrink/swell potential, as discussed in section six.

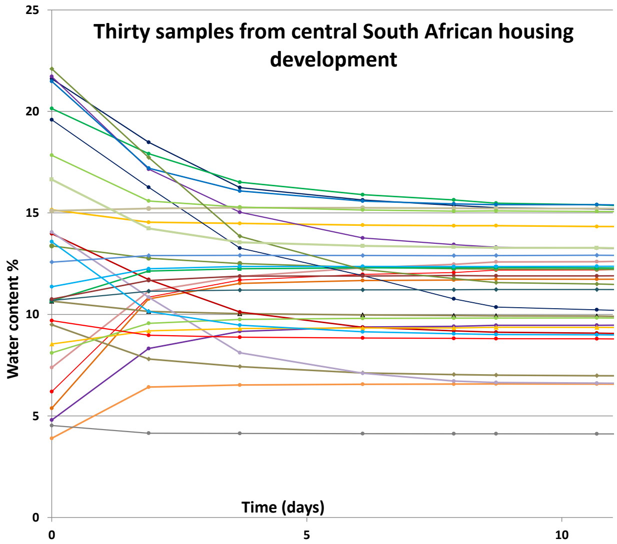

Figure 2 Thirty samples at 22MPa suction. Progress to equilibrium from natural moisture content

These 30 samples were used to probe questions concerning changes in suction due to conditions likely to be met in the lifetime of a structure (particularly prolonged rainfall and drought) and the possibility of change in suction potential due to oven drying of test specimens,. These questions are independent of the variability noted above and the conclusions are meaningful for individual or multiple samples of each soil. Figures 3 to 5 show these 30 samples being tracked from equilibrium moisture content at 22MPa, through oven drying and re-wetting by absorption of water from the air (Figure 3), wetting by the addition of a small amount of die-ionized water and re-equilibrating at 22 MPa (Figure 4), saturation with de-ionized water and re-equilibrating at 22 MPa (Figure 5).

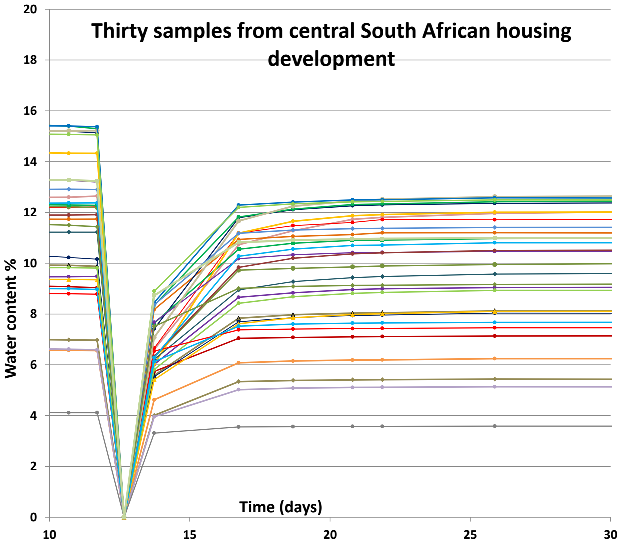

Figure 3 Thirty samples after oven drying

The equilibrium water retention at 22MPa suction is noticeably less after oven drying than before drying.

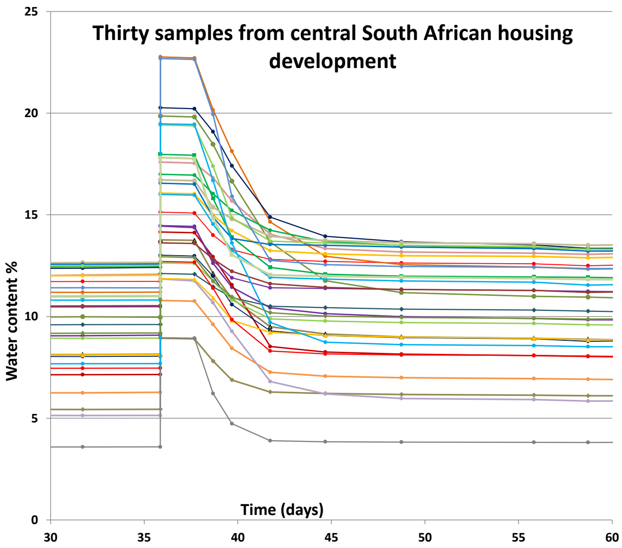

Figure 4 Thirty samples after partial wetting

Equilibrium water retention after wetting to close to natural moisture content is higher than before wetting, but not as high as before oven drying. Relative values of suction between the various samples remain quite similar.

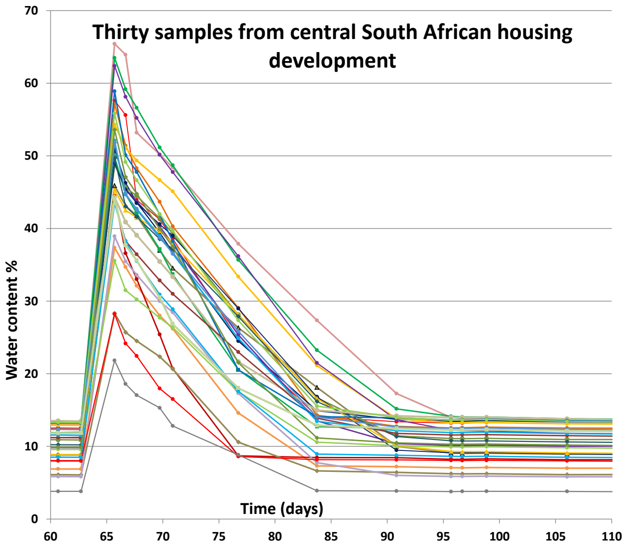

Figure 5 Thirty samples after saturation

The equilibrium water retention at 22MPa suction after saturation is higher than after partial wetting, but in most cases it does not reach the value attained before oven drying.

4.1 Discussion of results from this test

From initial (natural) moisture content the low-suction samples reached equilibrium moisture content after about 4 days, the high-suction samples reached constant water content after about 9 days. After oven drying and returning to 22MPa suction conditions, all samples reached equilibrium after about 5 days. This indicates that equilibrium is reached more quickly in gaining water content than in losing it. In most cases the equilibrium water content was significantly lower than that reached before oven drying. After wetting to water contents close to, or slightly higher than, the original values and re-stabilizing at 22MPa, all of the samples reached moisture contents higher than the value after oven drying, but some were substantially lower than the original values.

Following saturation, most of the samples reached equilibrium at somewhat higher moisture content, but lower than that reached before oven drying. Figure 6 shows moisture content changes as a bar chart. Samples whose initial water content was very low are grouped predominantly on the left side.

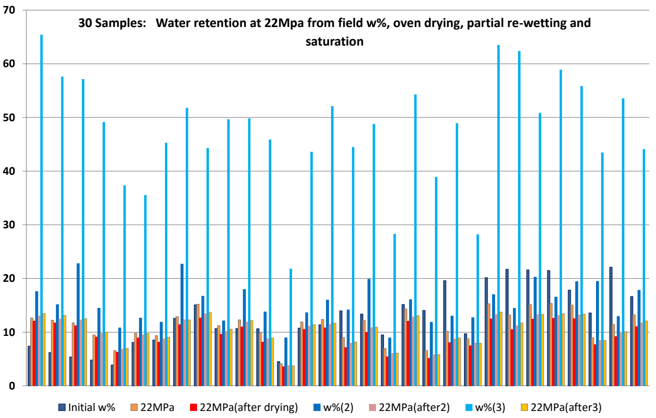

Figure 6 Water content reached by 30 samples at 22MPa from initial moisture content, after oven drying, after wetting and after saturation

Where the initial water content of the soil was well above its 22MPa value, oven drying significantly reduced the soil's subsequent suction potential, and even saturation did not restore the original suction potential. Where the initial water content was well below the 22MPa value, the soil was not so greatly affected by oven drying and saturation could lead to higher retained moisture content at 22MPa. This suggests that Blight's contention (Blight 2012) that air drying can lead to permanent changes in some residual soils may commonly apply to many, if not most, clayey soils. These points can be seen more clearly in Figure 6a, enlarged from the right hand side of Figure 6, and in Figure 6b, enlarged from the left hand side of Figure 6.

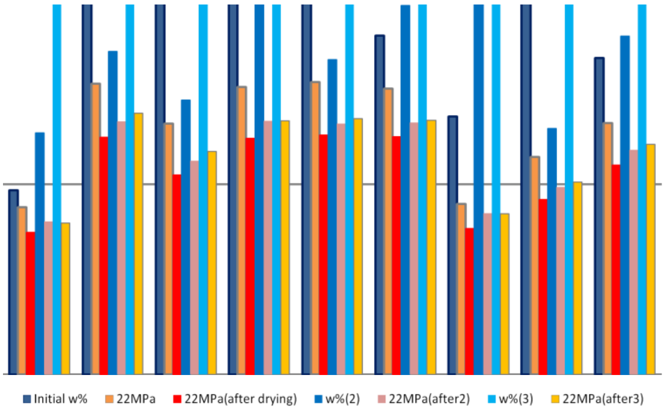

Figure 6a Samples with initial water content well above that at 22 MPa suction

Water retention after oven drying is considerably less than the value before drying and pre-oven drying water retention is not recovered even after full saturation. This suggests that the structure of the clay has been permanently changed by oven drying.

This test also suggests that in the majority of cases, whatever suction changes take place, the ratios of water content between the various samples remain substantially the same. The suction-history pattern moves up or down according to the general suction potential of the sample. In drought conditions soil suction can be expected to rise to 100MPa or more in some situations e.g. under the North side of a Southern hemisphere building (Bester et al. 2016). Oven drying might therefore not give a major distortion in many cases.

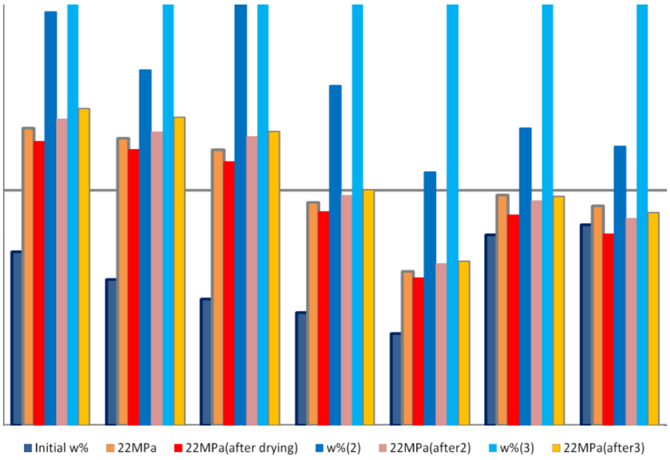

Figure 6b Samples with initial water content below that retained at 22 MPa suction

Water retention is only slightly less after oven drying and retention after saturation is usually greater than before oven drying. This suggests that part of the permanent structural change noted in oven drying had already been accomplished by field moisture conditions.

The consistent relationship over a wide range of suctions has been observed for hundreds of other samples besides those shown here, but some soils have been found which do not follow this pattern at very low suction/high water content values. High kaolinite content clays appear to retain more water at very low suction/high water content than would be expected according to the normal pattern. Some very high Cat-ion Exchange Capacity (CEC) clays tend to retain less water than expected according to the normal pattern at very low suction/high water content).

This occasional lack of conformity to pattern is likely to have little relevance for the problem of heaving foundations since it is generally high suction which causes shrink/swell problems. Kaolinite has low suction potential at any water content and is not known for causing shrink/swell damage. High CEC clays generally cause severe volume-change problems and the small reduction sometimes observed at high water content does not significantly change their problematic nature.

Of more relevance to the question of economically assessing expansive potential is the fact that equilibrium water content is reached far more quickly at high suctions than at low values. Equilibrium is also reached more quickly from initially dry conditions than from wet. This suggests that testing at fairly high suction from low initial moisture content could give useful results in an economic time-frame.

4.2 Reducing the time of testing by reducing sample size

It could be expected that smaller samples would take less time to reach equilibrium. Figure 7 shows small samples broken from one corner of a small clod of high plasticity clay from an electricity sub-station site in central South Africa. The samples were originally adjacent to each other in an attempt to eliminate variability in the material, so that difference in results would be attributable to sample size only.

Figure 8 shows plots of moisture content against time for seven different-sized small samples of the same clay (PI = 42) at 22MPa suction. The sample masses vary from 0.71g to 8.4g. All seven samples were close to equilibrium water content after one day in a climate chamber at 22 Mpa. Equilibrium value reached by the 7 samples averaged 13.56% with standard deviation of 0.30 giving a Coefficient of Variation (COV) of 2.2. The correlation coefficient with sample-size was 0.17, suggesting that there is no significant correlation between sample size and test outcome for this range of sample masses.

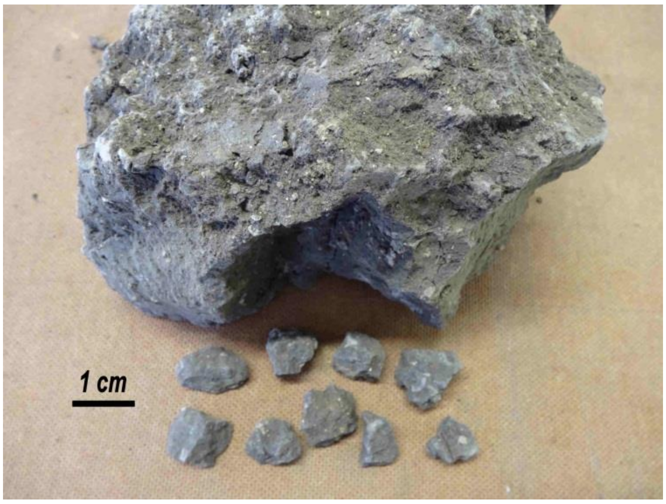

Figure 7 Small samples broken from a small clod of clay

Samples tend to break along existing planes of weakness and their structure and fabric are likely to be similar to that of the original sample. Such simple preparation takes little time and leaves little opportunity for short-cuts in preparation, which is widely thought to be a cause of inconsistent results in many kinds of tests.

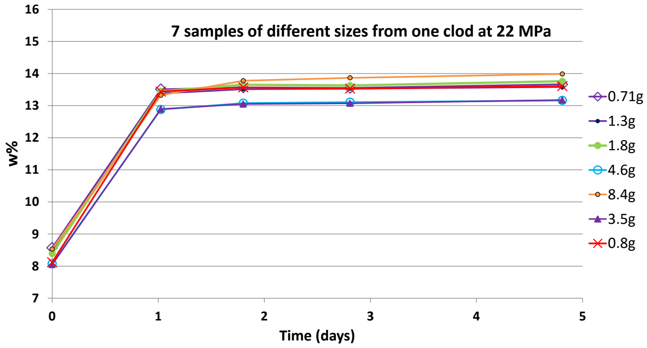

Figure 8 Equilibration of 7 samples (0.71g to 8.4g) at 22 MPa suction

5. ASSESSMENT OF LIKELY SOURCES OF ERROR

The range of variation in the above test raises the question of the accuracy of the experimental procedure. Reliability of the method depends on accuracy in weighing. The aspect of the procedure most likely to involve weighing error is the determination of the oven-dry mass. To assess the probable errors in this, samples of 10 different soils were oven dried and the change in weights after leaving the oven were tracked until equilibrium mass was reached. The loading plate of the balance was protected with an expanded polystyrene pad to reduce conduction of heat into the balance and hence reduce temperature induced errors. The enclosure around the loading plate was closed to reduce convection current effects and the samples were taken through the weighing procedure as quickly as possible to minimize temperature change effects in the balance. Samples were repeatedly weighed in sequence until all showed equilibrium of readings. Results are plotted in Figure 9.

In the cooling of the sample containers from oven drying temperature (105^{o}C) to room temperature the change of weight of air in the container must be accounted for since the ground glass lids of the sample bottles are not air-tight against the pressure differential developed in the cooling process. The volume of the sample containers was measured to be 70 ml. The density of dry air at 105°C is 0.0009217 g/ml, giving the weight of air in the container as 0.0645g. At the ambient temperature at the time of the test (25°C) the density of dry air is 0.001196 g/ml giving the weight of dry air in the container as 0.0837g. Relative humidity in the laboratory was 36%. The adjustment required for density to take account of water vapour at this humidity is 0.000003 g/ml giving a weight adjustment of 0.0002g The change in weight due to air density factors could therefore be expected to be 0.0837 + 0.0002 – 0.0645g = 0.0194g.

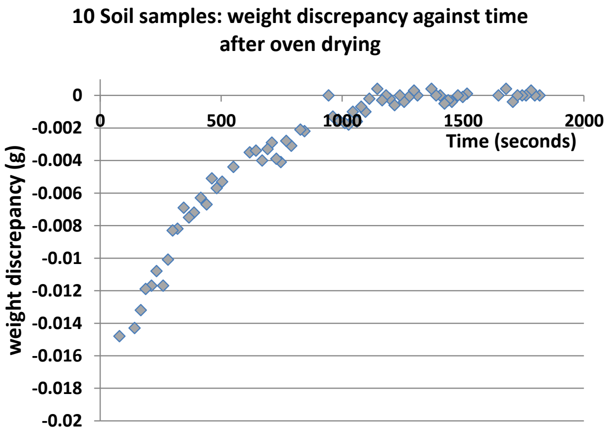

Figure 9 Progress towards constant temperature of 10 samples from oven drying

Extrapolating to time of leaving the oven shows a gain in weight up to a constant value of about 0.019g after about 1500 seconds (25 minutes).

Similar tests were performed on three more sets of ten samples. All showed similar results and it was concluded that if samples were weighed after 25 minutes of cooling at ambient temperature with lids closed the results were likely to be accurate to within 0.001 g. The smallest sample mass in the test under review was 0.7129g. An error of 0.001g could account for an error of 0.14% in moisture content. This does not account for the observed range of almost 1%.

A second possible source of error is the leakage of water vapour into or out of the weighing bottles while closing the lids on removal from the constant suction container before weighing. Samples were usually dealt with in batches of 20. Closure was always performed with both hands to halve closure time. The time to close the lids of all 20 samples was usually 18 seconds, and it is unlikely that the time could have reached 25 seconds in any test. On six occasions the first sample of a batch was transferred immediately from the constant suction container to the balance. Figure 10 shows change in mass with time for a sample left with lid open for 3 minutes. Throughout this time the loss of water vapour was fairly constant at approximately 17.9 x10^{-6} g/s.

The rates for the six samples were: 10.9 x10^{-6} g/s,17.9 x10^{-6} g/s, 14.8 x10^{-6} g/s, 9.5 x10^{-6} g/s, 12.5 x10^{-6} and 13.6 x10^{-6} g/s (average 13.2 x10^{-6} g/s). The maximum observed rate of moisture loss was 17.9 x10^{-6} g/s, which would mean the loss of 25 x 17.9 x10^{-6} g = 0.0004g for the last sample closed at the slowest probable handling rate (25 s.).

A third possible source of error is transfer of water vapour to or from the atmosphere due to imperfections in the air-tightness of the ground glass lids of the sample bottles. After removing 20 samples from the constant suction chamber and closing all lids, 330 seconds are typically required to weigh the 20 samples. It is conceivable that the procedure might take 500 seconds if unfavourable conditions led to unusually slow stabilization of the balance.

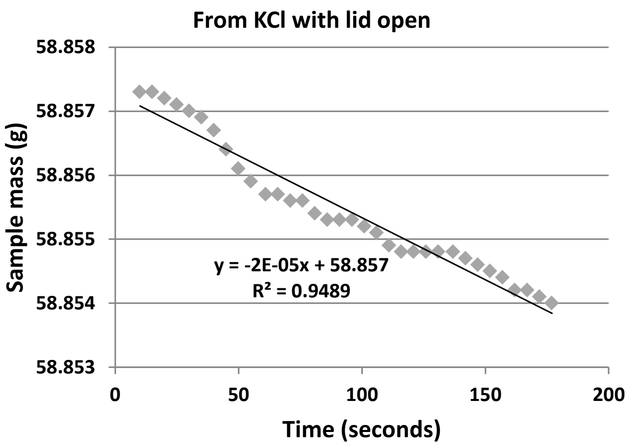

Figure 10 Loss of weight due to loss of water vapour with the sample bottle open after removal from a sealed container of saturated KCl solution to an analytical balance

This possible source of error was examined by repeated sequential weighing of 10 samples after removal from an atmosphere of KCl and closing the lids of the sample bottles. The procedure was similar to that illustrated in Figure 9, where progress towards equilibrium was plotted until constant mass was achieved. Figure 11 shows the results of this investigation.

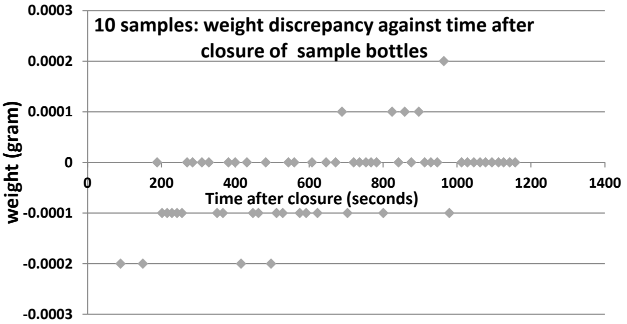

Figure 11 No clear trend of either losing or gaining weight is discernible

The majority of readings start and remain at the equilibrium value. Results not at the equilibrium value are all within 0.0002g of that value. The balance reads to 0.0001g; the pattern of results suggests that the balance may have an accuracy of +/- 0.0002g and that in the 20 minutes duration of the test transfer of moisture to or from the closed bottles was not large enough to be demonstrated by this balance.

Although tests performed over periods of the order of 20 minutes did not detect a clear pattern of water vapour movement into or out of the container, it has been observed that over a period of several days there is certainly such movement and the samples gradually move towards equilibrium with ambient conditions.

The fourth possible source of error considered was inaccuracy of the balance itself. The balance used throughout these tests has an internal calibration mass and can be set to check consistency by weighing this mass ten times and assessing the standard deviation in the ten values. The consistency was checked periodically throughout the tests. The reported standard deviation was typically 0.00005g, and in all cases less than 0.0001g. As an additional check, two empty sample bottles were weighed repeatedly, two weighing sequences for each bottle. In no case was any measurement more than 0.0001g above or below the dominant value. From this it would appear that the balance readings are probably accurate to +/- 0.0001g if good laboratory technique is followed.

Following these investigations into likely accuracy, a test was run where samples were closed and weighed alternately in ascending and descending numerical order on removal from the constant suction environment. It was expected that there might be small relative displacements between alternate measurements for the first and last closed samples due to the considerations illustrated in Figure 10. The resulting retention values can be seen in Figure 12, where the alternately first and last sealed and weighed samples for one of the soils have accentuated markers. Part of the plot after stability was reached is magnified at the lower part of the figure (where the curves of other samples have been omitted for clarity).

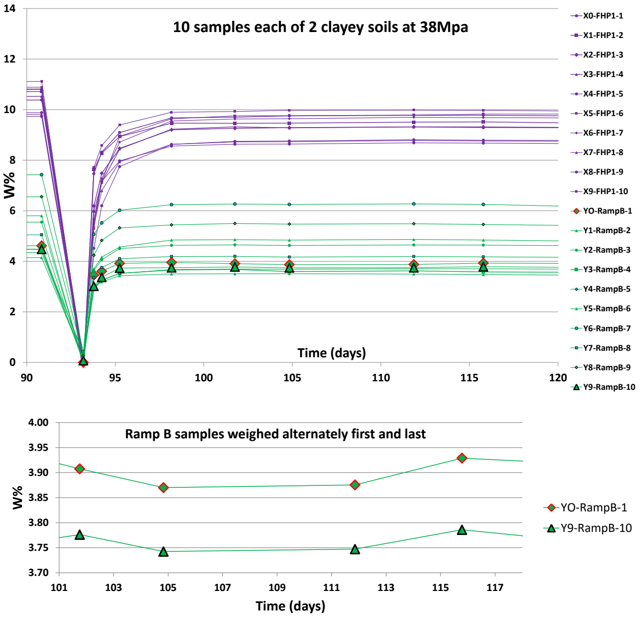

Figure 12 Samples tested with containers closed in alternately reversed order before weighing. Part of the graph is magnified (below) where only the first and last closed values for one of the soils are shown

It might have been expected that a slight, alternating narrowing and widening of the gap between first and last samples would result from water vapour loss in the 18 seconds between closures. From the average rate of loss determined above this might be expected to be about 0.0004 g. The dry weights of the first and last samples were 1.8656g and 2.0735g respectively. Allowing for possible balance errors of 0.0001g in worst combination this would suggest a likely change in water content of no more than 0.032%. Without allowance for worst-case balance error the likely change expected would be not more than 0.021%. The plots in Figure 12 show variations of about 0.05% in which the values for the samples move largely in sympathy. This suggests that limiting factors for accuracy may not depend on mass measurement considerations but rather on considerations like lack of constancy in temperature and humidity control. Nevertheless, it appears that the method is capable of distinguishing between suction potentials of different soils and different samples of the same soil to a high degree of accuracy. It also appears capable of detecting variability in suction potential of a particular soil over a very small spatial range.

6. ASSESSMENT OF VARIABILITY OF SOIL PROPERTIES

Variability of soil properties has been noted by many observers, e.g. Singh and Lee (1970), Minty et al (1979), Phoon and Kulhawy (1999a), Phoon and Kulhawy (1999b), Jaksa (1995). There appears to have been relatively little heed paid to this observation by many practicing engineers. Little attention is usually drawn to it in tertiary level geotechnical engineering courses or popular text books. It has been suggested that variability in measured properties may be due to differences in operator technique and laboratory processes (Minty et al. 1979), or careless laboratory procedures (Jakobsz and Day 2008).

Figure 12 shows effective suction potential for two soils which received practically identical treatment and minimal preparation by one operator. They show substantial variability between individual samples and one soil shows more than twice the variability of the other. This suggests that variability may be a property of the soil rather than an artefact due to poor testing procedures. Whatever the reason for variability it is clear that it must play a role in the soundness of geotechnical design. The field of Reliability Based Design (RBD) has been developed to provide a rational way of taking variability of various kinds into consideration in assessing the probability of success or failure of geotechnical designs. Coefficient of Variation (COV) is a fundamental input to RBD. COV is defined as standard deviation divided by mean expressed as a percentage. COV is typically assessed by considering variability across soils databases and across testing methods for the property under consideration rather than being sample specific. Hence rather crude approximations are commonly used. For example Phoon and Ching (2013) give a range (in their Table 1) of mean for PI of clay and silt (10-40) and guideline estimate of COV as (3-12%)/mean. Such empirical estimates imply considerable lack of precision and could be a contributing factor to reluctance towards application of RBD in engineering practice. The small-scale suction testing procedure described here allows an assessment of actual sample-specific variability relatively quickly and easily. The authors have related such specific assessments to some engineering projects and the following brief case studies illustrate that they can be of value in practical situations even without rigorous application of RBD.

6.1 Five brief variability case studies

Case1. Five test pits were dug in a geotechnical investigation at a building site in Central South Africa. A layer of clearly identifiable dark brown residual clay was evident in four of these pits. Five samples each from the first two pits were tested by small-scale suction tests. They showed a COV of 27. Five samples from each of the other two pits were tested. They showed a COV of 25. The COV of the combined 20 samples was 27. Figure 13 shows the combined values. It appears that high variability may be a consistent property of this soil and was taken into account in the design of the new structure. When access roads were constructed near this site several years ago the roads developed an undulating profile. Removal of underlying clay was needed to reach an acceptable standard. Early appreciation of the variability of the material could have led to its removal initially and saved considerable expense.

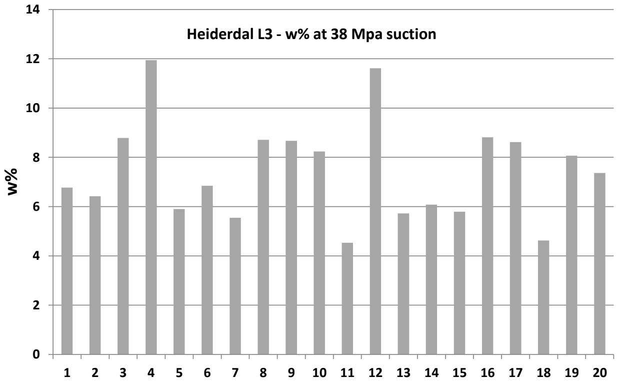

Figure 13 Water Retention at 38 MPa suction for 20 samples from a layer of residual clay in 4 test pits

Case 2. A similar situation was noted at a road project on a somewhat similar geological formation some distance away. It is illustrated in Figure 14. Undulations in the road indicate wide variation in expansive potential of the sub-grade. Tests on soil from an adjacent housing project which has suffered significant heave damage showed substantial variability in suction potential.

Figure 14 Undulations in a road close to a housing project where heave damage occurred and variability in suction potential was found to be substantial

Case 3. Samples were taken from the proposed site of an electricity sub-station in Central South Africa. A clod from this site was used for the test of Figure 7. Samples were broken from adjacent locations on one lump of soil in an attempt to eliminate variability of material so that the effect of sample size only would be assessed. Water retention at 22MPa varied by a little under 1%, showing a co-efficient of variation (COV) of 2.2.

Ten samples from a test pit at this site were tested. A COV of 2.4 was found in a test at 22Mpa suction. Ten samples from a second test pit on the site were tested. A COV of 2.5 was found when tested at 22Mpa and also when tested at 140 MPa. Results are shown in Figure 15 and Figure 16. Low variability appears to be a consistent property of this soil. All values indicated high expansive potential. Foundation indicator tests were performed on a number of samples and all tests indicated high expansive potential with very little variability. The foundation was designed accordingly and no significant problems occurred. This suggests that where variability is low, current methods of design may be adequate.

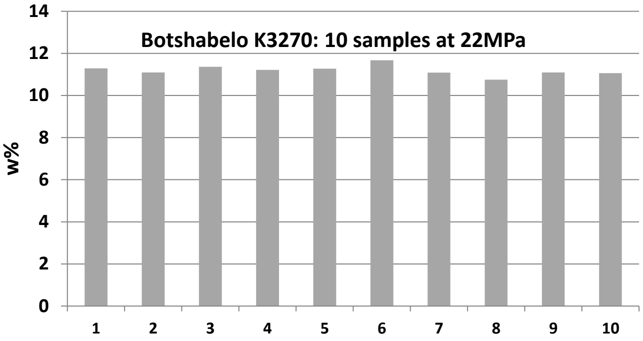

Figure 15 Water retention at 22 MPa from one test pit at an electricity sub-station in central South Africa

This clay gave almost the same COV from three different scales of distribution and suggests a possible fractal aspect to variability.

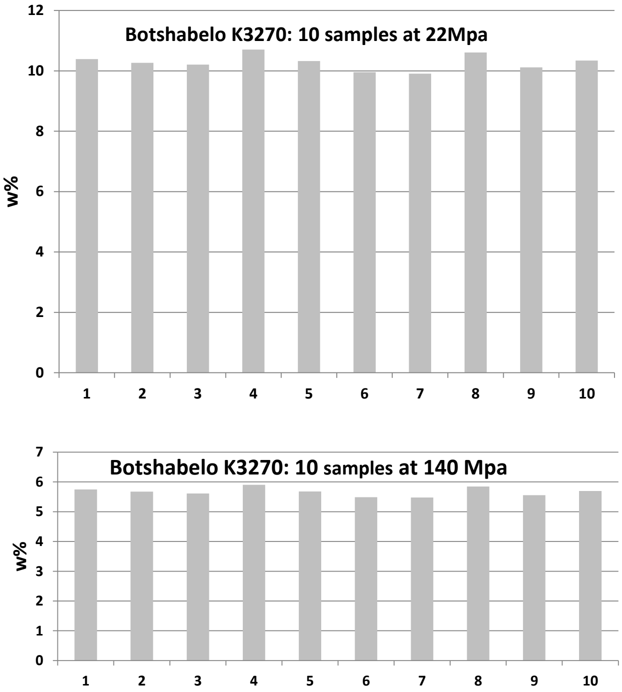

Figure 16 Water retention at 22 MPa and 140 MPa for the same clay layer as Figure 16 in the second test pit at an electricity sub-station site in Central South Africa. COV is 2.5 in both cases

Case 4. A less fortunate situation occurred at a sub-station in Northern South Africa. Normal foundation indicator tests were performed on samples from a test pit at the site. The tests indicated non-expansive soil and the foundations were designed accordingly. Shortly after completion serious heave damage occurred. Suction tests on samples of the soil concerned gave results as in Figure 17.

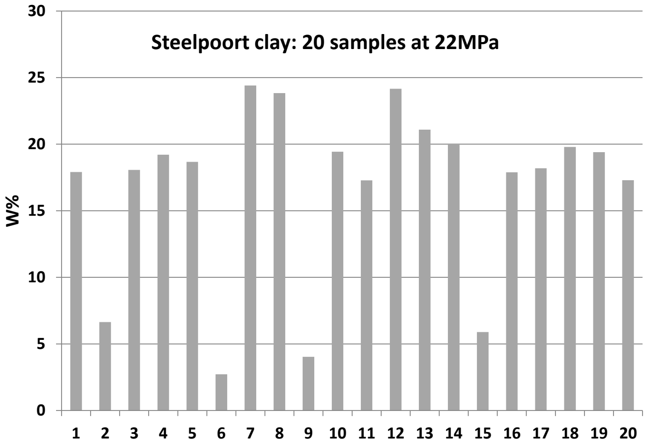

Figure 17 Variability of suction potential is very high

The COV for these 20 samples is 39. It appears that the common practice of relying on results from a single sample could lead to very unsound design.

Samples of this clay were sent to seven reputable soils testing laboratories for foundation indicator tests. PI is the most commonly used property for indicating shrink/swell potential.

Figure 18 shows values of PI from these seven laboratories. It is evident that the original tests on which the foundations were designed happened to be from a very unfortunately chosen sample. The resulting damage might have been avoided if the exceptionally large variability had been assessed and allowed for in the design process. It is doubtful whether RBD would have given satisfactory results using the estimated COV from Phoon and Ching (2013) as in section 6 above.

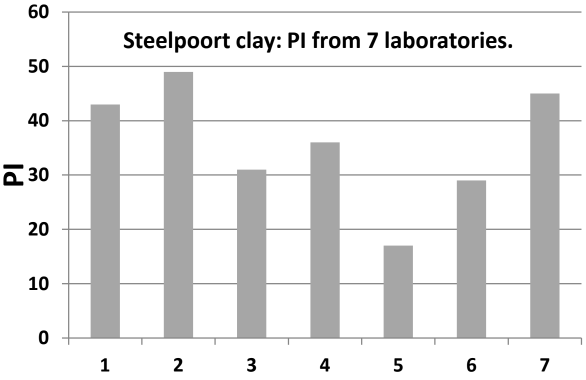

Figure 18 COV for PI of 7 laboratories is 34, in good agreement with 39 from a considerably larger sample space of suction values

It is far more convenient to assess 20 samples by suction tests than to send multiple samples for duplicate testing.

Case 5. A house was built close to a test pit where laboratory results indicated no risk of heave. Following rain the house suffered such severe heave damage that it had to be demolished before the roof was installed. Suction tests showed COV 16, very similar to the soil of Figures 19 and 20. The sample tested in the geotechnical investigation was again unrepresentative of the general ground conditions. Suction tests would have given warning of this and almost certainly have led to better foundation design.

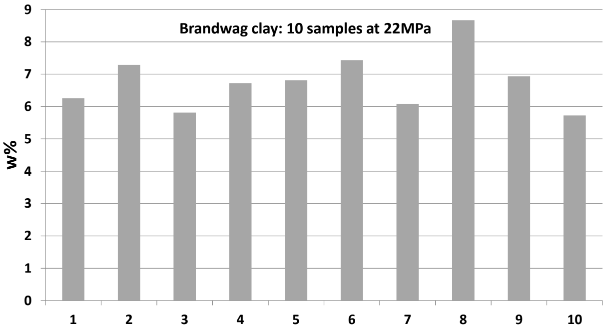

Figure 19 COV of 13 for 10 suction test samples of typical clayey soil from Central South Africa

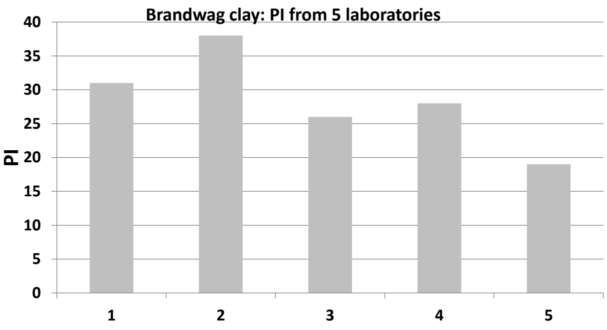

Figure 20 COV for PIs from 5 different laboratories is 17 – again close to the value from suction tests on a bigger sample space

6.2 General observations on variability

Cases 3 and 4 above represent opposite ends of the variability spectrum. Very few soils so far tested by this technique, have had COV smaller than 2 and none greater than 39.

Values from a more typical soil are illustrated in Figures 19 and 20. This soil is from a building site in Central South Africa. Not all correlations with multiple laboratory PI tests are as close as this, as might be expected in view of the weaknesses noted in section 2 concerning the reliability of Atterberg limits for predicting heave. Figure 21 shows 8 samples from a roads project tested at 8 different testing laboratories and also in 8 suction tests – the commercial laboratory results show COV of 29 where the suction tests show COV of only 20. Both sets of results are, however, adequate to give warning of the danger of basing design on one set of test results.

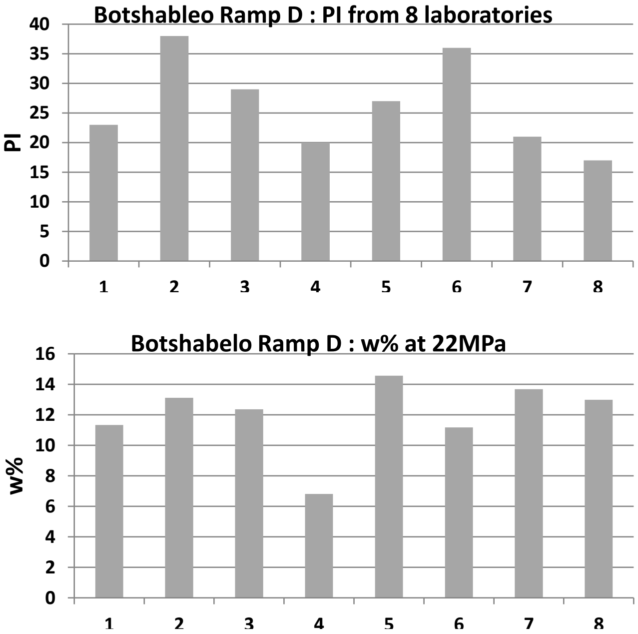

Figure 21 PI and water retention values for a clayey soil from a Central South African road project. COV from 8 laboratories (above) is 29. COV from 8 suction tests (below) is 20.

7. CONSIDERATIONS FOR ASSESSMENT OF SHRINK / SWELL POTENTIAL

In order to assess shrink/swell potential across a wide range of soils in a consistent and systematic manner two factors need to be considered: a standard suction at which to measure water retention, and a consistent approach to hysteresis

7.1 Suction value for measurement

Factors influencing the choice of standard suction value should include convenience, time taken to reach equilibrium, ease of attaining acceptable accuracy and cost. Stable water retention is achieved quickly at high suctions and slowly at low suctions but water content is low at high suctions and therefore more precision is required in weighing samples. Figure 22 shows plots of equilibrium water retention over the full suction range relevant to soil mechanics for 5 sets of 4 samples through one drying and wetting cycle. These are effectively soil water characteristic curves plotted with linear scales. The SWCC is commonly drawn with semi-log scales. As Blight pointed out (Blight 2013), log scales give a much distorted view of reality and linear scales allow a better understanding of the true situation. From these plots it appears that at very high suctions (greater than about 150MPa) all of the plots take on steeper gradients and converge, so that the spread of water content becomes inconveniently small. From about 20MPa to 120MPa the plots have only a small gradient and remain at a fairly constant spacing. From about 20MPa to 0MPa the curves rise at a very steep gradient, indicating that water content determination may be inconveniently sensitive to accuracy in suction measurement.

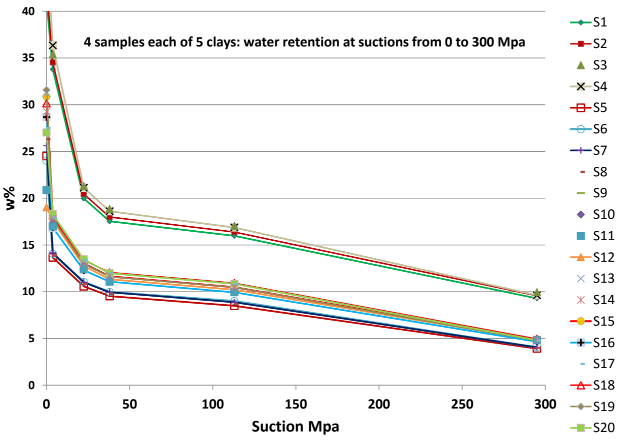

Figure 22 Water retention : suction for 5 clayey soils

From these plots it appears that low suctions may be a poor choice for standardization from the points of view of both excessive testing time and sensitivity to suction. The ideal range appears to be in the region of 20MPa to 100MPa, where sensitivity to suction and testing time are both favourable. For equilibrating samples over saturated solutions of known suction it appears that NaCl would be a very good choice. It is cheap, readily available, non-toxic and needs no handling precautions. Its suction value is close to 38 MPa throughout the temperature range from 15^0C to 25^0C. This is also a very convenient suction for the climate chamber, since temperatures close to ambient require a relative humidity of only 75% for 38 MPa suction and this poses negligible risk of condensation problems. KCl would also appear to be suitable, with a saturated solution providing 22MPa over the same range of temperature.

7.2 Hysteresis

To give comparable results across different samples the question of hysteresis needs to be considered. Figure 23 shows water retention for samples of 20 different soils at 22MPa suction after the samples started wet and dry. The difference in retention varies from about 10% to 30%, with most fairly close to the average of 20%.

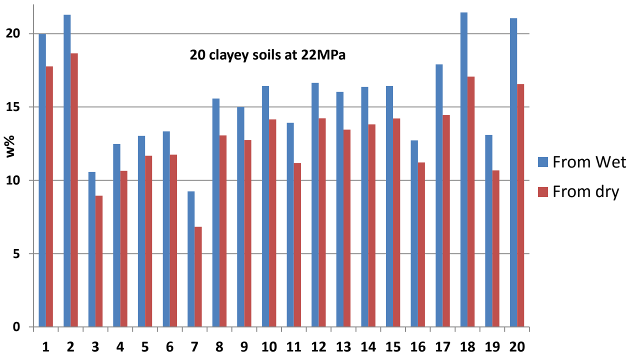

Figure 23 Water retention differences at 22MPa due to hysteresis

For the purpose of assessing potential shrink/swell it might be preferable to start from the shrinkage limit of the soil or from the

driest condition the soil is likely to experience in the lifespan of the structure concerned. In the sub-humid and semi-arid conditions where shrink/swell problems are usually most severe suction values can be very high during periods of drought. For convenience and uniformity, values used in this paper are from oven dry unless otherwise indicated.

8. CONSIDERATIONS FOR ASSESSMENT OF VARIABILITY

Table 1 shows COVs for 13 soils at 3 suctions. Due to the excessive time taken, only 1 set was tested at very low suction. COV does not seem to be sensitive to suction value; all measured values are within 1.2 of the average, most are within 0.5. The most suitable range for evaluating shrink/swell potential (section 7.1) appears to be also suitable for COV. It should therefore be feasible to perform one test for both shrink/swell and variability. The table deals with the typical range of variability for Central South African clayey soils tested to date. About half of them show COV indicating that multiple sample testing is essential for accurate shrink/swell evaluation.

Table 1 COV: 10 samples of 13 soils

Soil	0MPa	22MPa	38MPa	180MPa	Average
Vrede 6	10.8	10.6	10.0	/	10.5
Big Lump	/	1.9	1.5	1.7	1.7
Belcher 2	/	15.3	15.1	15.2	15.2
Lerato P 1	/	10.5	10.9	10.7	10.7
Lerato P 2	/	5.2	6.0	5.2	5.5
Fichardt P	/	5.0	5.8	5.6	5.5
Botsha R	/	19.4	18.9	22.0	20.1
Botsha B	/	2.8	2.6	3.3	2.9
Dersley	/	7.1	7.0	7.1	7.1
BK 3270	/	2.3	2.3	2.4	2.3
Cecelia 5A	/	7.4	7.5	7.6	7.5
Cecelia 5B	/	14.2	14.0	14.4	14.2
Brandwag	/	13.0	13.6	13.4	13.3

9. CONSIDERATIONS FOR DESIGN

Variability of shrink/swell potential appears to hold out far greater risk for design than high shrink/swell potential alone. In the cases encountered in practice, some of which have been presented in section 6.1, where foundation indicator tests have pointed to high expansive potential and variability was low, foundations were designed for high swell and suffered little significant damage. Where high variability exists, but variability was not taken into account, substantial damage occurred.

How then should design proceed for a soil with significant shrink/swell potential? It would be possible to do multiple tests and then design for the most unfavourable value found. This should be much safer than accepting the value from only one set of tests. The design might, however be over-conservative and unnecessarily expensive. It would appear that the only rational method, for which a reasonable assessment of acceptable risk can be made, is reliability based design. Small scale suction testing can give sample specific values relatively easily and there may be a good fit between RBD and these tests in such cases.

10. TESTING PROCEDURE

The following procedure (as shown in Figure 24) is suggested as providing a balance between speed, simplicity, ease of preparation, economy of apparatus and reliability of results.

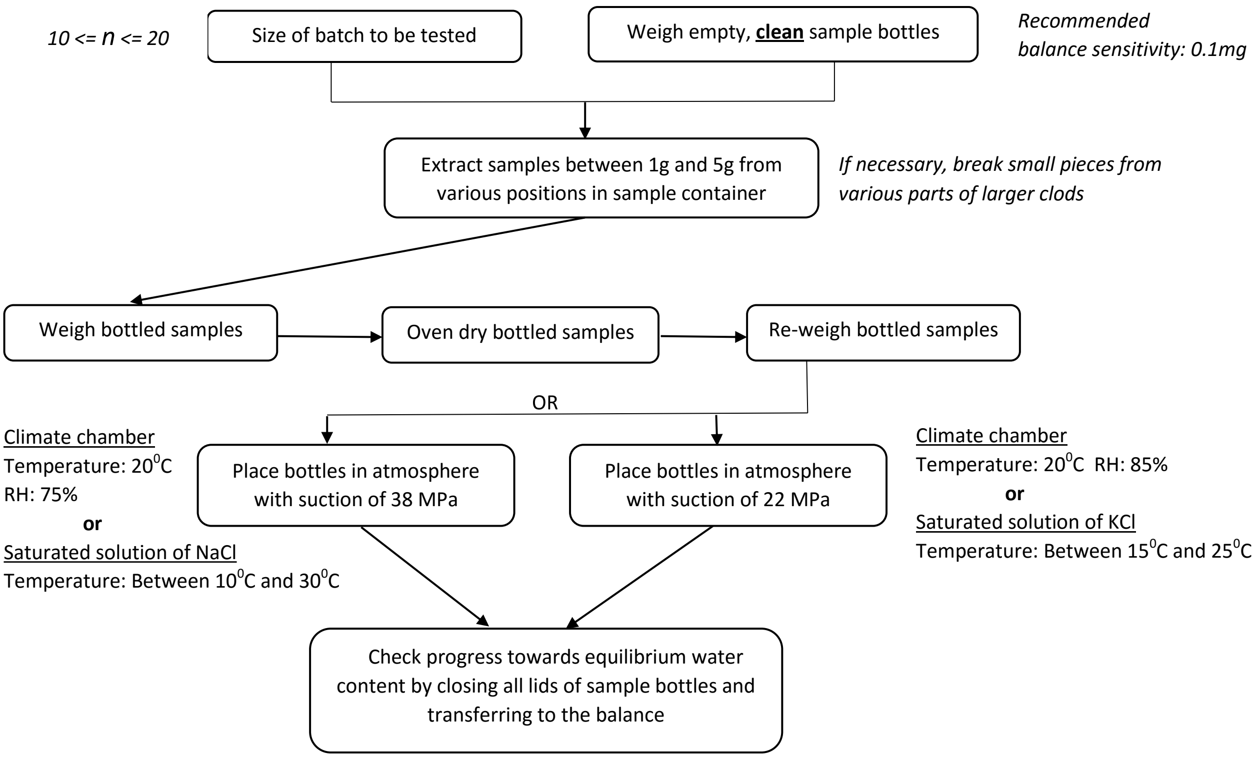

Figure 24 Flow Chart showing the Procedure of a balance between speeds, simplicity, ease of preparation, economy of apparatus and reliability of results

Three days may be required to approach within 1% of equilibrium value, and 5 days may be required for effective equilibrium over saturated solutions. Equilibrium is reached in noticeably less time in a climate chamber.

At 38 MPa, water retention below 4% corresponds with low swell potential; retention above 10% corresponds with high swell potential; retention above 13% corresponds with very high swell potential. At 22 MPa water retention below 5% corresponds to low swell potential; retention above 12% corresponds with high swell potential and above 16% corresponds with very high swell potential. COV greater than 15 may indicate more troublesome shrink/swell problems than high expansive potential alone.

11. CONCLUSIONS

Moisture retention at an applied suction appears to be a good indicator of shrink/swell potential although it may not be an indicator of other soil properties such as shear strength. The testing technique described here, using very small samples subjected to easily-controlled suctions, may provide a more convenient and reliable means of assessing probable shrink/swell potential than current commercial methods. Very little sample preparation is involved and there is little scope for short-cuts which may adversely affect results. The soil micro-structure remains substantially intact.

A large enough number of test samples can be used to gain insight into the variability of the soil concerned without greatly increasing the testing time or labour cost. A measure of the variability of individual soils can be of value in indicating cases where current testing procedures give inadequate warning of shrink/swell problems. Specific COV values for individual soils provided by this method could make RBD a very attractive tool for design in a field well known for widespread failures following traditional design procedures.

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