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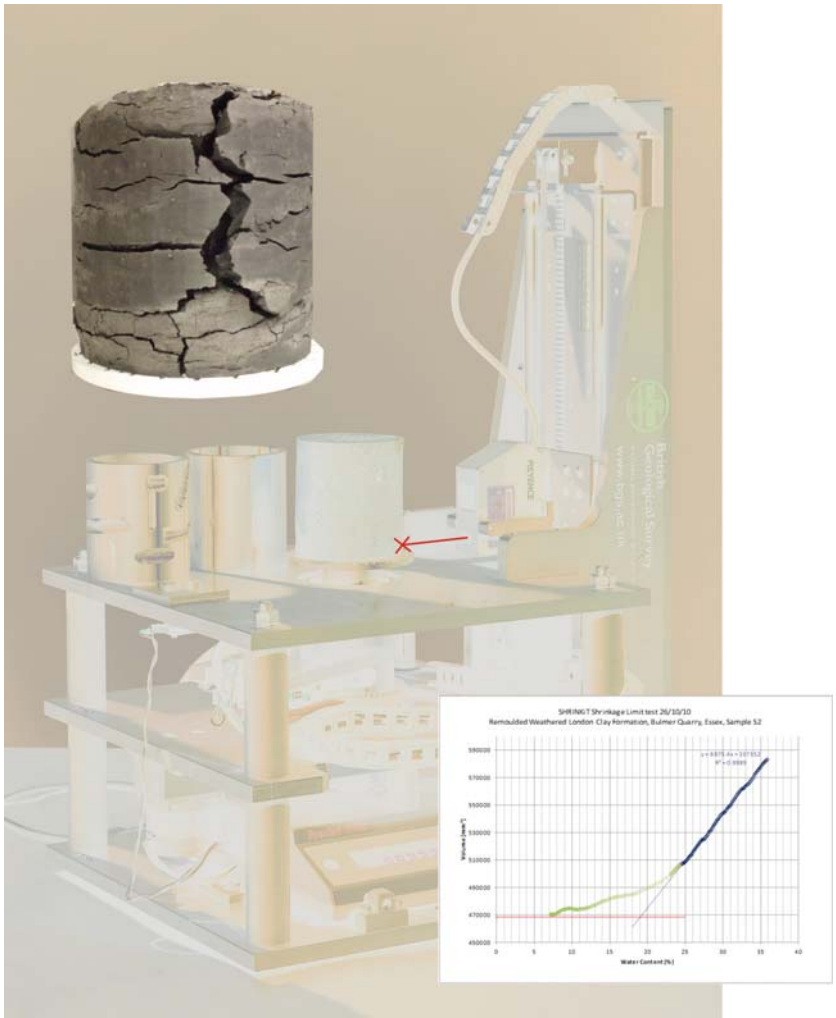
SHRINKiT: Automated measurement of shrinkage limit for clay soils

Land Use, Planning & Development Programme

Internal Report IR/10/077



BRITISH GEOLOGICAL SURVEY

LAND USE, PLANNING & DEVELOPMENT PROGRAMME
INTERNAL REPORT IR/10/077

IR/10/077

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SHRINKiT (v.2) apparatus

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Foreword

This report is the published product of a technological development by the British Geological Survey (BGS) of a new automated apparatus and method for the measurement of the shrinkage limit of a cylindrical clay soil specimen in the laboratory.

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Summary

This report describes the development at the British Geological Survey (BGS) of a new automated apparatus, titled 'SHRINKiT', for measuring the shrinkage limit of a clay soil. This has been developed at the BGS's geotechnical laboratories, in part with NERC Innovations funding. The new method is intended to replace two British Standards (BS1377) methods which have fallen into disuse at BGS, in common with many other laboratories in the UK, and to some extent worldwide, partly as the result of safety concerns in their required use of large quantities of mercury. During the test the cylindrical specimen is allowed to air-dry and shrink. The apparatus carries out repeat measurements of diameter, height and weight; the dimension-measuring component being in effect a simple laser scanner. Each test takes a few days to complete; the duration depending on specimen size, soil type, initial water content and environmental conditions. The output of the test is a plot of water content vs. volume from which the shrinkage limit of the soil can be calculated using the graphical construction method described in BS1377. The shrinkage limit is defined as the water content below which there is little or no further structural shrinkage of the soil. Additional information may also be obtained from the results. The test may be carried out on a wide variety of soil types in an undisturbed, remoulded or compacted state.

1 Introduction

Shrinkage is the process whereby a reduction in water content of a clay soil results in a reduction in its volume. Clay shrinkage is a key factor in much building and infrastructure subsidence damage in Britain and worldwide, and therefore should be of interest to civil engineering in general, and to the building industry in particular. Costs of hundreds of millions of pounds sterling are incurred every year in Britain alone. During years characterised by drought costs rise sharply. In the field of geotechnics little work has been carried out to characterise the shrinkage behaviour of susceptible geological materials, principally clays and mudrocks, in their natural state.

This report describes an accurate and automated laboratory shrinkage limit measurement system for testing engineering clay soils, developed at the British Geological Survey's geotechnical laboratories between 2000 and 2010. It also describes the subject background and other research carried out worldwide, mainly in the field of 'soil science'. This includes both laboratory test methods and mathematical models used to characterise the shrinkage curve. The BGS SHRINKiT automatic shrinkage limit measurement system was developed from a manually-operated apparatus first designed in 1994, and trialled until 2000. The system was developed in order to solve several practical problems associated with the existing British Standard tests (BS1377:1990, Part 2, Tests 6.3 & 6.4) for the determination of shrinkage limit, including an important health and safety issue regarding the handling of significant quantities of mercury. The report also examines the literature on shrinkage testing, and initially reviews current thinking about the soil-water systems and their relation to various 'limit' parameters including the well known liquid limit and plastic limit.

The BGS SHRINKiT was awarded Natural Environment Research Council (NERC) 'Innovations A' funding in 2008 (IP 621) and 2009. The current version of the apparatus (v.2) can be considered as a fully operational prototype. Future developments are likely to include reductions in size and cost, and research into the viability of an accelerated test where the specimen is isolated from atmospheric conditions and subject to controlled drying conditions, resulting in increased specimen throughput. The report considers the relative merits of different test methods, calibration of the apparatus and the errors involved.

2 The soil-water system

The shrinkage limit is the least familiar of a trio of Atterberg limits, the others being liquid limit and plastic limit, which apply to fine-grained engineering soils. All three are specific water contents defined by simple internationally standardised laboratory tests. Each is intended to represent, albeit approximately, a point of significant change in the mechanical behaviour, usually taken to relate most closely to shear strength, of the soil as the water content is changed. The properties of a clay soil at various water contents are shown in Table 1. *Swelling is the reverse of shrinkage, as an increase in water content results in an increase in volume. The processes of shrinkage and swelling of natural clay soils are not reversible.*

Table 1 Limiting water contents of a soil-water system (after Sridharan & Prakash, 1998a and ELE International, 1998)

Phase	SOLID	SEMI-SOLID	PLASTIC	LIQUID-PLASTIC	LIQUID	SUSPENSION
Water	← Water content decreasing →					
Atterberg Limits	**w_S**		w_P STL	w_L WSL		WFS
Condition	Stiff - v. stiff	Stiff -workable	Sticky	Slurry		Suspension
Strength (kPa)	← Shear strength increasing →		150?	1.5?	(0 – 1.5)?	
Shrinkage*	Residual	Normal	Structural			
		AE	SWL			

Key:

w_L	Liquid limit (%)
w_P	Plastic limit (%)
w_S	**Shrinkage limit (%)**
AE	Air entry point
STL	Sticky limit (%)
SWL	Swelling limit
WFS	Free-swell limit (%)
WSL	Settling limit (%)
*	(Braudeau et al., 1999)

Soils that contain clay minerals have the physical property of plasticity. Plasticity may be defined as the ability of a material to change shape continuously under the influence of an applied stress (Reeves et al., 2006). The plastic limit is defined as that water content below which the soil is not plastic; that is, it crumbles when stress is applied. The liquid limit is generally taken as the boundary between 'plastic' and 'flow' (or 'liquid') behaviour (Yong & Warkentin, 1975). It is interesting to note that the plastic limit varies very little between common soil types compared with the liquid limit, and not in proportion to clay mineralogy (inter-particle forces have a more prominent role in determining the liquid limit). The same may be said of the shrinkage limit.

2.1 THE SHRINKAGE LIMIT

The shrinkage limit was one of five state limits conceived in 1911 by Albert Atterberg, a Swedish chemist and agronomist, and was originally termed the 'cohesion' limit (Casagrande, 1948; Sridharan & Prakash, 1998a/b). The laboratory apparatus and procedures for carrying out some of the 'limit' tests were later refined by Arthur Casagrande. Currently, it is one of three established Atterberg limits, but is the least well known and tested. The shrinkage limit may be defined as the maximum water content at which little or no volume change of the soil mass takes place on further drying (Reeves et al., 2006). This represents the point where inter-particle shearing resistance equals the maximum capillary force (Sridharan & Prakash, 1998a). These authors also suggest that two other fundamental limits apply: the 'free-swell limit' and the 'settling limit', and that the latter is a true representation of liquid limit ("*real* liquid limit"); that is, it more closely indicates the change from liquid to plastic states than the conventional liquid limit.

Table 2 BS standard index limits, and non-BS (italics) (Sridharan & Prakash, 1998a; Yong & Warkentin, 1975; Head, 1992)

LIMIT	PHASE	WATER	STRENGTH	SHRINKAGE.
Free swell	Suspension		Zero	No shrinking
Settling	Liquid / plastic	Max capacity	Zero	Little or no shrinking
Liquid	Liquid ~ plastic		1.5 kPa ?	Shrinking
Sticky	Plastic	Partial saturation	?	↓
Plastic	Plastic ~ semisolid	↓	150 kPa ?	
Shrinkage	Solid ~ semisolid		?	Little or no shrinking

The paper showed that the settling limit was typically half as much again as the liquid limit. If correct, this represents a considerable water content difference for highly plastic clay. This work was partly based on viscometer testing. It is generally accepted that the shear strength at the plastic limit is approximately 100 times that at the plastic limit. However, the strength boundaries shown in Table 1 and Table 2, though much quoted, are approximate; for example at the liquid limit shear strength has been shown to vary between 0.5 and 5 kPa (Sridharan & Prakash, 1998a). The fact that the soil at its liquid limit has measurable shear strength suggests that it cannot represent the precise boundary between liquid and plastic states. The 'free-swell limit' was proposed to represent total loss of shear strength and also the onset of self-weight consolidation. The 'sticky limit' is the lowest water content at which the soil adheres to metal tools, and is determined by an empirical test (Head, 1992), which has largely fallen into disuse. The sticky limit is closely related to the surface chemistry and spacing of the clay minerals (Yong & Warkentin, 1975).

The 'swelling limit' and 'air-entry point' are used in soil science, and are described by Braudeau et al. (1999). The 'air entry point' is the minimum water content at which a sample remains saturated under atmospheric conditions, while the 'swelling limit' is the boundary between structural and normal shrinkage; normal shrinkage representing the case where overall shrinkage is proportional to water loss and structural shrinkage representing the case where it isn't, but is rather due to structural changes in the soil. The shrinkage interpretation shown in Table 1 is one of many critically reviewed in Braudeau et al. (1999) and Cornelis et al. (2006).

2.2 SOIL SUCTION

Shrinkage of a clay soil is produced by an increase in soil suction. Soil suction ψ consists of two components: matric suction, defined as the difference between the pore air pressure, u_a and the pore water pressure, u_w and osmotic suction, π

Thus:

$$\psi = (u_a - u_w) + \pi$$

Matric suction develops as the meniscus of the outermost wetted front within the test specimen can only be maintained by an increasing surface tension as pore water evaporates during air-drying. Whilst the SHRINKiT apparatus does not measure it, suction within soil specimens can be measured using a pressure (extractor) plate apparatus, psychrometer or tensiometer. In the case of a pressure plate test (Figure 1) the specimen is subjected to an air pressure differential across a semi-permeable membrane, equivalent to applying a suction, which allows water to be expelled from the specimen but without air replacing it. In the case of clay soils this results in shrinkage but without the evaporation produced by drying as per the shrinkage limit test. In practice it is

difficult to do a pressure plate test on a clay soil because the specimen tends to lose contact with the semi-permeable plate or membrane as the specimen deforms during the test.

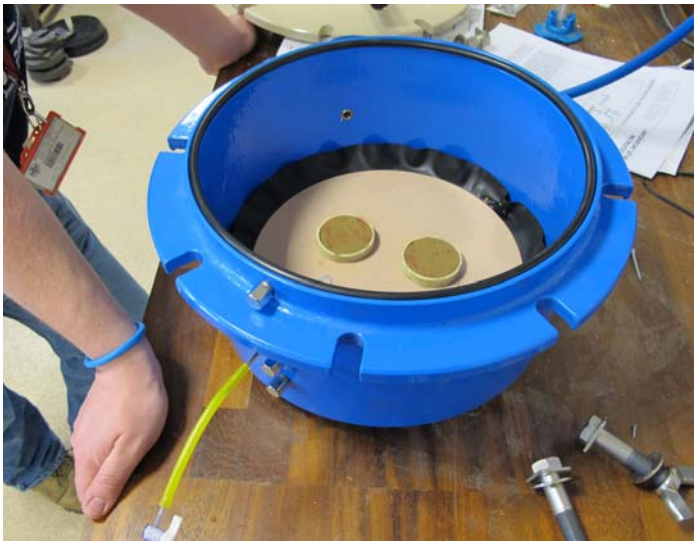

Figure 1 Pressure (extractor) plate apparatus (ceramic plate type) with lid removed showing two test specimens.

Theoretically it should be possible to combine the result of a pressure plate test with that of a shrinkage limit test (e.g. SHRINKiT) for the same soil type (Fredlund et al., 2000). The output of the pressure plate test is a plot of suction vs. water content whilst the output of the shrinkage limit test is a plot of volume (or density of voids ratio) vs. water content. It should therefore be possible, for the same soil type, to replace the water content in the pressure plate plot with voids ratio from the shrinkage limit test.

Alternatively, the following relationship is postulated by Fredlund et al. (2000):

$$\frac{de}{dw} = \frac{\frac{de}{d\psi}}{\frac{dw}{d\psi}} = \frac{a_m}{b_m}$$

Where e is voids ratio, w is water content, ψ is suction, and the Van Genuchten parameters a_m and b_m are the gradients of the suction vs. voids ratio plot (shrinkage limit test) and the suction vs. water content plot (pressure plate test), respectively. However, it should be noted that the suction vs. water content relationship for a pressure plate test on a given soil is not unique but exhibits hysteresis (Harrison & Blight, 2000). This would presumably also apply to the voids ratio vs. water content plot for the shrinkage limit test should it be possible to perform a 'wetting' leg in addition to the normal 'drying' leg.

At low suctions macro pores are the first to lose water. With increasing applied suction the water in micro pores, and ultimately adsorbed water layers on individual soil particles, are lost. This appears to have been confirmed by Harrison & Blight (2000) who found that at low suctions (<10 kPa) void size distribution most influenced capillary tension, whereas at higher suctions (>100 kPa) clay mineralogy took over. This was the conclusion drawn from correlations between suction vs. water content gradients and particle size distribution and plasticity.

3 Review

A review of shrinkage and swelling test methods was made by Hobbs & Jones (1995), and a review made during the early phase of the project by Jones (2001). This report highlighted the great variety of tests carried out worldwide, and the interpretation of these and established index tests. Sridharan & Prakash, (1998a) showed the importance of the shrinkage limit as a fundamental soil mechanics parameter. However, the development at the BGS of a national geotechnical database as part of the 'UK Rocks and Soils' project has shown that there is an almost total absence of directly measured shrinkage limit data in British-based geotechnology and site investigations. The lack of a safe and accurate test method for shrinkage limit is probably an important reason for this. Much scientific data relating to swell/shrink of clay soils has been reported in the journal of the Soil Science Society of America. A great deal less has been reported in the geotechnical / civil engineering literature. During the 1980's and 1990's research was carried out, in the soil science field, particularly in France, USA, Holland, Belgium, Australia and Africa, which led to many new methods and refinements of earlier ones. One new method in particular which most closely resembles SHRINKiT was that of Braudeau et al. (1999). However, unlike SHRINKiT this method used a batch technique and much smaller 'plug' specimens. This technique derived from a significant body of work from around the world, principally in the fields of soil science and agronomy, examining curve-matching methods to define mathematically the shrinkage curve of a soil and hence its hydro-structural and agricultural properties (McGarry & Malafant, 1987; Cornelis et al., 2006). During the early 2000's worldwide soil science research has further refined the analytical methods for defining the 'soil shrinkage characteristic curve' or SSCC. This attempts to relate water content to pore volume, rather than bulk volume, during shrinkage.

Oren et al. (2006) and Puppala et al. (2004) described an image analysis method for measuring the laboratory shrinkage of a cylindrical specimen of compacted clay landfill liner. This method used a single camera allied to digital image analysis techniques that depended on the identification of the edges of the specimen's silhouette as captured on calibrated digital photos. The method described in Oren et al. (2006) and Puppala et al. (2004), developed initially from triaxial test monitoring, dealt specifically with volumetric strain associated with clay liner desiccation, and did not discuss shrinkage limit. It was similar in principle to SHRINKiT. However, the image analysis method did not allow for depressions in the surface of the specimen, for example as shown in the calibration piece (Figure 21), to be correctly measured, and would thus probably be unsuitable for many undisturbed samples. Additionally, the version described was also not automated.

Cornelis et al. (2006) provided a useful review of test methods and also of analytical models with which to define the soil shrinkage characteristic curve (SSCC). The methods considered are summarised in Table 3. These authors also carried out comparative tests on a vertisol and a lixisol. Of the methods reviewed, the 'core' methods of Berndt & Coughlan (1976) and Hanafy (1998) most closely resembled the kind of test familiar to geotechnologists, as they dealt with undisturbed core containing structural discontinuities. As such, it was probably also the method most useful to geotechnologists. However, the method was rather crude in that shrinkage was measured using callipers, and for some reason the core was confined within a liner. The other two methods used relatively small clods containing little or no soil structure, i.e. they consisted mainly of soil matrix where the macrostructure of the soil had been destroyed. The reason for the soil scientists' preference for the latter was that it allowed specific matrix-related properties to be determined without the 'distraction' of near-surface voids such as root-holes, burrows, fissures etc. These methods did not, however, allow the anisotropy of natural shrinkage or the role of void development, collectively referred to as the "geometry factor" (Cornelis et al., 2006), to be measured.

Table 3 Principal methods of shrinkage test used in soil science to determine the SSCC
(adapted from Cornelis et al., 2006)

Test method	Reference	Specimen type
Core method	Berndt & Coughlan, 1976	Undisturbed core
Core method	Hanafy, 1998	Undisturbed disc
Balloon method	Tariq & Durnford, 1993	Disturbed clod
Paraffin coated method	Lauritzen & Stewart, 1941	Disturbed clod

The multi-equation models which have been used in soil science to characterise, by means of 'curve-matching', the SSCC curve are summarised in Table 4. The rating scale of Cornelis et al. (2006), in terms of accuracy and mathematical efficiency, has been adapted to show A = good to C = poor. For the purposes of geotechnology the modified Chertkov (2000) and Groenevelt & Grant (2001) models probably have the most application.

Table 4 Principal types of analytical model used in soil science to determine SSCC
(adapted from Cornelis et al., 2006)

Method	Reference	No. of parameters	Equations	Rating
Bea	Braudeau et al.	7	Exponential	A1
ModC	Chertkov (modified)	4	Linear	A1
ModGG	Groenevelt & Grant (modified)	4	Exponential	A1
MM1	McGarry & Malafant	6	2nd order hyperb.	A2
MM2	McGarry & Malafant	4	Exponential	B
Kea	Kim et al.	4	Exp./linear	B
TD	Tariq & Durnford, 1993	7	3rd order polyn.	B
OH	Olsen & Haugen	6	2nd order hyperb.	B
Gea	Giraldez et al.	2	3rd order polyn.	C

Clay shrinkage is a key factor in much building & service subsidence damage in Britain and worldwide and therefore should be of interest to civil engineering in general, and to the building industry in particular. Annual costs of around £300 million are incurred every year in Britain alone (ABI, 2004; Jones, 2004). During a year characterised by drought this figure rises sharply. Current global warming predictions show wetter winters (20% increased rainfall) and drier summers (30 % reduced rainfall) for much of the UK (UKCIP, 2004). Despite this, little effort is currently put into measuring directly the shrinkage (or swelling) properties of soils; rather, simple relationships with familiar 'index' tests, notably plasticity index (the difference between the liquid and plastic limits), and linear shrinkage are used. However, these index tests use remoulded samples & do not reflect the structure, fabric, or stress history of the soil in its natural state. Hence correlations of this type are often very generalised and inadequate at a local scale. What little shrinkage testing that is done in Britain uses a mercury bath apparatus (Figure 3), which is the 'definitive' British Standard method (BS1377; 1990; Part 2, Test 6.3). The use of the 'subsidiary' British Standard test for remoulded samples (BS1377: 1990; Part 2, Test 6.4), which also employs mercury immersion though on a smaller scale, but in a less controlled environment, is more widespread worldwide (Figure 4). However, due to the significant health hazard of mercury, both in its liquid and vapour phases, many geotechnical laboratories worldwide ban its use and cannot therefore make use of these tests.

Where the BS test procedure is in use, as formerly at the BGS, stringent precautions should be taken, particularly relating to ventilation, spillage, storage, and disposal. However, as a persistent and bioaccumulative toxic substance mercury should be removed from purposeful use, and hence the environment, by source reduction and its replacement by alternative technologies and substances. Compared with most other industrial applications, where mercury is present as an ingredient or in small components, for example batteries, switches, and lamps, the current BS1377 test methods use relatively large quantities of the substance in a manner liable to evaporation and spillage.

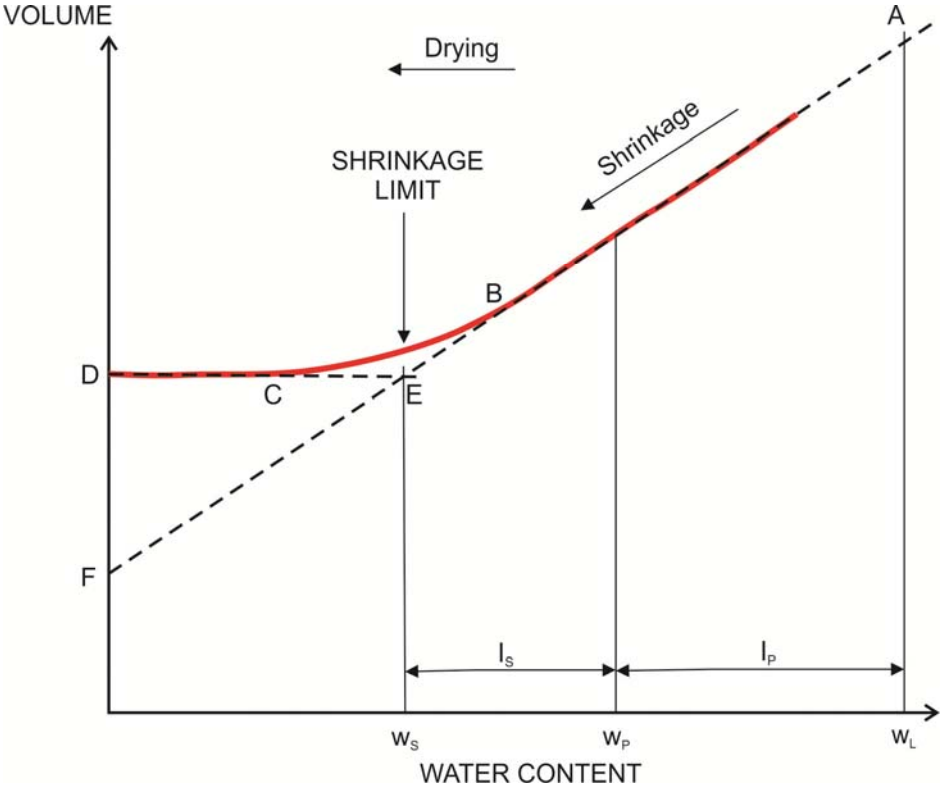

Figure 2 Idealised plot of Volume vs. Water content, showing shrinkage limit construction and liquid and plastic limits (BS1377: 1990)
NOTE: w_L = liquid limit, w_P = plastic limit, w_S = shrinkage limit, I_P = plasticity index, I_S = shrinkage index

The shrinkage limit test, in all its forms, measures the reducing volume of a small specimen of soil at several points during the drying process. From the water content vs. volume (or density) plot the 'shrinkage limit' is then calculated using a prescribed graphical construction that essentially pinpoints the stage beyond which little or no further volume reduction occurs; the reported shrinkage limit being the water content at this point (Figure 2). The 'SHRINKiT' does this using a form of laser scanning, whilst at the same time allowing the specimen to be accurately weighed without the need to remove it from the apparatus for each weighing (with the exception of the final oven-dried weighing). The results of the two methods appear to be comparable, based on trials with the original manual version 1 (Hobbs & Jones, 2006). However, the 'SHRINKiT' is also capable of performing functions which the BS tests and other immersion methods cannot (e.g. measurement of anisotropic behaviour). Whilst such features are probably of more interest to researchers than to the building industry, they should throw more light onto the mechanisms and controlling factors of shrinkage and onto the differences between 'undisturbed' and 'remoulded' shrinkage behaviour.

The shrinkage curve represented in Figure 2 shows the main elements of the process. In practice the experimental curve (red line) starts at some point between the liquid and plastic limits, as it is not possible to test a specimen at or near the liquid limit. The initial straight part of the curve (A

to B) covers the 'structural' and 'normal' shrinkage stages referred to in Table 2 whilst the lower curved part covers the 'residual' shrinkage stage (B to C). The curve is completed by oven drying (C to D). *The use of the term 'constant volume' is not necessarily accurate in all cases and should perhaps be referred to as 'minor volume reduction'.* The Shrinkage index, I_S is the 'shrinkage' counterpart of the more familiar Plasticity index, I_P and is defined as follows:

$$I_S = w_P - w_S$$

The British Standard 'definitive' method (BS1377; 1990; Part 2, Test 6.3) describes an apparatus developed in Britain by the Transport Research Laboratory (TRL) in the 1960's (Ackroyd, 1969), which uses mercury immersion in a special vessel and Archimedes' principle to measure volume reduction due to shrinkage (Figure 3). According to BS1377, this 'definitive' test is usually carried out on an undisturbed sample, but may also be used for remoulded or compacted samples. In practice it is better suited to remoulded specimens. This device is currently marketed by Bellstone Hi-Tech (India). There is a second, 'subsidiary' British Standard test (BS1377; 1990; Test 6.4), designed for remoulded samples, which uses what is referred to as the 'prong plate' apparatus (Figure 4). However, this also uses a mercury bath and is based on American Society for Testing & Materials (ASTM) and American Association of State Highway & Transportation Officials (AASHTO) methods (D427-04 and T92-97, respectively) (ASTM, 2007). This apparatus is currently manufactured or marketed by ELE International (UK), Humboldt Mfg. Ltd (USA), Heico (India) and Shambhavi Impex (India).

The 'definitive' method differs from the 'subsidiary' method in that volume measurement is made using a micrometer attached to an electrical circuit, which senses the meniscus of the mercury in the specially designed vessel. The 'subsidiary' method is crude, the specimen volume being measured by weighing the overflow during immersion in a calibrated dish. The 'subsidiary' method is also not suitable for undisturbed samples. Both tests should be carried out in a fume cupboard. The storage and disposal of mercury-contaminated samples remain problematic.

Figure 3 'TRL' shrinkage limit test apparatus (BS1377; 1990; Part 2, Test 6.3)

Figure 4 'ASTM' 'prong plate' shrinkage limit test apparatus (BS1377:1990, Part 2, Test 6.4)

Definitions: Geotechnology

Liquid limit, w_L

Plastic limit, w_P

Shrinkage limit, w_S

Plasticity index, $I_P = w_L - w_P$

Liquidity index, $I_L = \frac{(w - w_P)}{I_P}$

Shrinkage index, $I_S = w_P - w_S$

Shrinkage ratio, $R_S = \frac{m_d}{V_d}$

(Where: m_d is oven-dried weight, V_d is oven-dried volume)

Volumetric shrinkage, $V_S = \frac{(w - w_S)}{R_S}$

(Where: w is initial water content)

Voids ratio, $e = \frac{Vv}{Vs}$

(where Vv is volume of voids, Vs is volume of solids)

Suction, $\psi = u_a - u_w$

(where u_a is pore air pressure & u_w is pore water pressure)

Definitions: Soil science:

Moisture ratio, $\vartheta = \frac{Vw}{Vs}$

4 The SHRINKiT apparatus

SHRINKiT is the name given to a new automated geotechnical laboratory apparatus and method for determining the shrinkage limit of clay soil specimens. In addition, it is capable of defining an important part of the so-called 'soil-water characteristic curve' of volume change or 'shrinkage curve' for a soil, and providing further useful information regarding anisotropy and structural or lithological controls on volume change; an example being the influence of remoulding on shrinkage behaviour by means of paired 'undisturbed' and 'remoulded' test specimens.

The apparatus was first developed in a manually-operated form in 1994 (Figure 5) (Hobbs et al., 2000), and subsequently an automated version was designed in 2000 (Figure 6) and developed to its current state, referred to as SHRINKiT, between 2000 and 2012. This report describes the latter, a schematic diagram of which is shown in Figure 8. The SHRINKiT apparatus produces data for two parameters: specimen weight and specimen volume; the former a direct measurement and the latter a calculation based on the measurements of specimen height and specimen diameter. The amount of data gathered during the test is determined by the operator at the outset.

The apparatus is capable of testing undisturbed, remoulded, or compacted cylindrical specimens of around 100 x 100 mm size (precise dimensions are not essential). The result of the test is a plot of Volume vs. Water content from which the shrinkage limit is calculated by graphical construction, in the same way as for the British Standard test methods (BS1377; 1990). The difference is in the way the plot is derived. A schematic of this plot is shown in Figure 2.

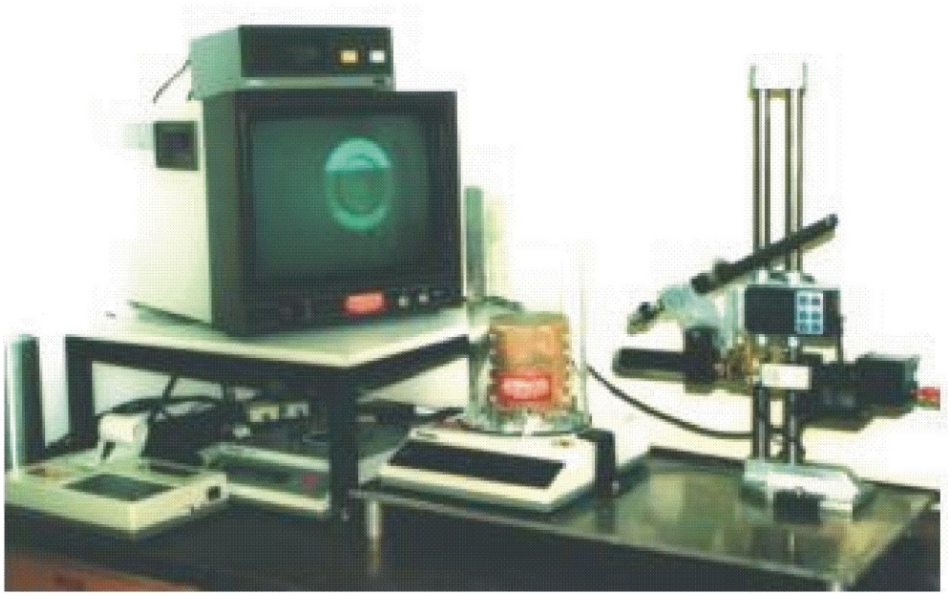

Figure 5 BGS Shrinkage limit apparatus [version 1: manually-operated]

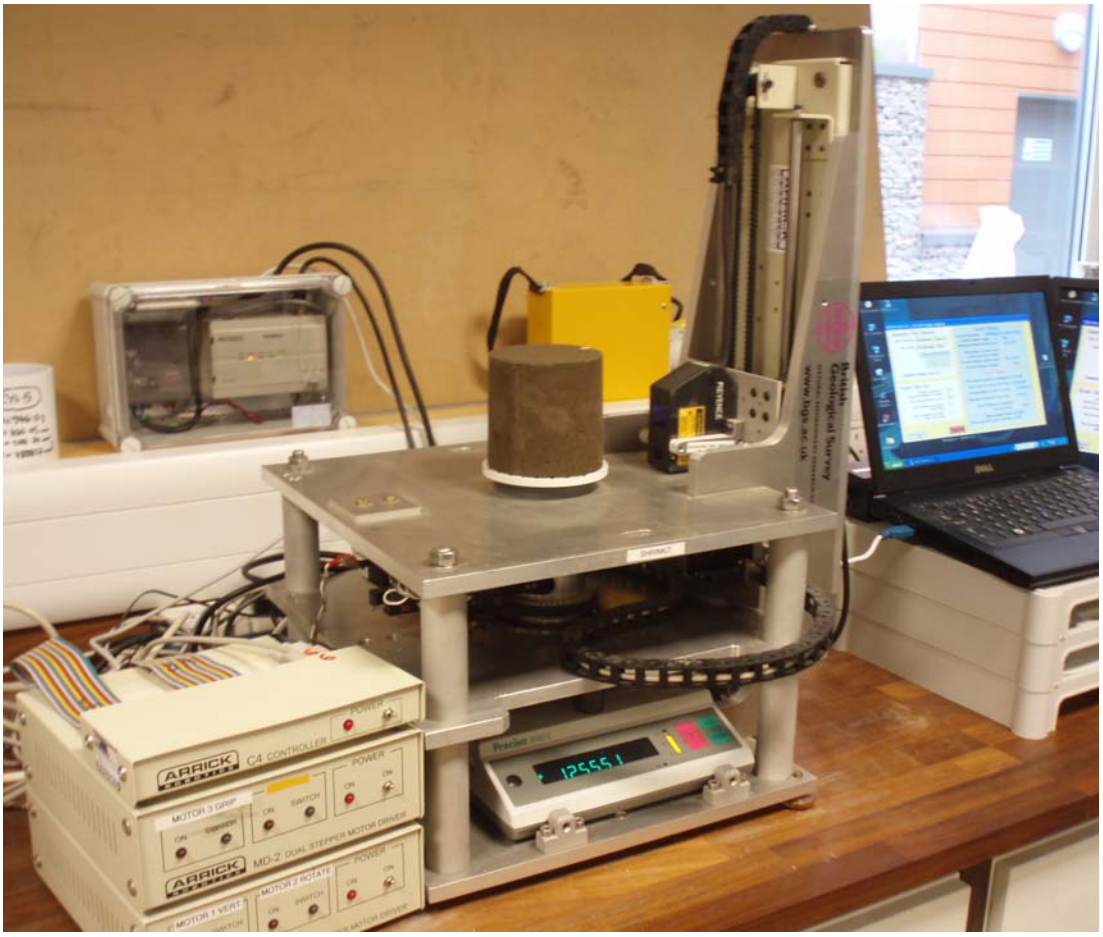

Figure 6 Shrinkage limit apparatus [version 2: fully automated, 'SHRINKiT'] 2012

A key difference between version 1 (Figure 5) and version 2, SHRINKiT (Figure 6), is that the former 'tracks' the changing positions of a small number of discrete targets attached to the test specimen, whereas the latter 'scans' the specimen with vertical points spaced proportionately to specimen height (Figure 7). These locations and spacings are determined by the geometry of the moving components and pre-defined by the operator. They are not attempting to 'track' particular points on the specimen.

The SHRINKiT apparatus employs a laser range finder to measure both the change in diameter and the change in height of a cylindrical test specimen (the second laser positioned to measure specimen height directly, shown in Figure 6, is for evaluation purposes only and is not logged as part of the test). The laser currently in use is a *Keyence LK081* CCD targetless laser displacement transducer, with resolution 3 µm and range 65 to 95 mm. It is aligned horizontally and travels in a vertical plane on a belt-driven carriage, while the specimen rotates independently in a horizontal plane. At all times the laser is at a fixed distance (119.35 mm) from, and aligned with, the turntable's axis. This is referred to as the 'range constant'. Edge-recognition algorithms in the software allow the height of the specimen to be determined using the vertical carriage zero position as a datum (problems of top edge recognition with irregularly shaped specimens are addressed in section 8.2). Below the rotating table is a release mechanism (gripper), rotating on a system of special concentric bearings, which allow the specimen to be weighed on a 3.1 kg capacity *Precisa 3100C* electronic balance before and after each scan cycle. The movements of laser and specimen are driven by two *Arrick Robotics* belt-driven stepper motor assemblies, types *X9* and *RT12* respectively, each fitted with a 1:4 ratio belt-driven gear box. The release mechanism is controlled by a third stepper motor unit, type *GR2*. The motors are controlled, and the laser and balance read, by a custom *Visual Basic version 6.0* program via a *Measurement Computing* (USB-1608FS) data acquisition unit and two Serial/USB convertors. Details are

given in section 8 and in Gunn (2001) and Roberts (2010). Control and logging are determined by the following factors:

- Turntable rotation increment (> 3 degrees) i.e. the cylindrical segment width,
- Vertical scan increment (3<n<30) i.e. the number of intervals top to bottom, and
- Scan rate (up to 6 per hour depending on scan density) i.e. the number of complete volume determinations.

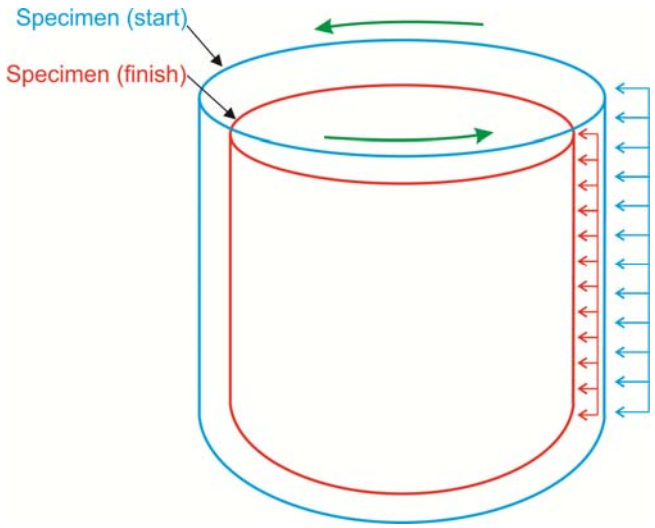

Figure 7 SHRINKiT's proportional distribution of vertical scan points (in this case 12)

The above factors allow for a maximum number of scan points per scan of 3,510. The duration of each scan depends on the rotation and vertical increments selected. A scan with 3,510 points takes approximately 40 minutes to complete. The final stage of the test requires the removal of the specimen for 24 hours oven drying at 105 ^{o}C and return to SHRINKiT for the final (water content = zero) scan. The specimen does not have to be returned to exactly the same position on the pedestal.

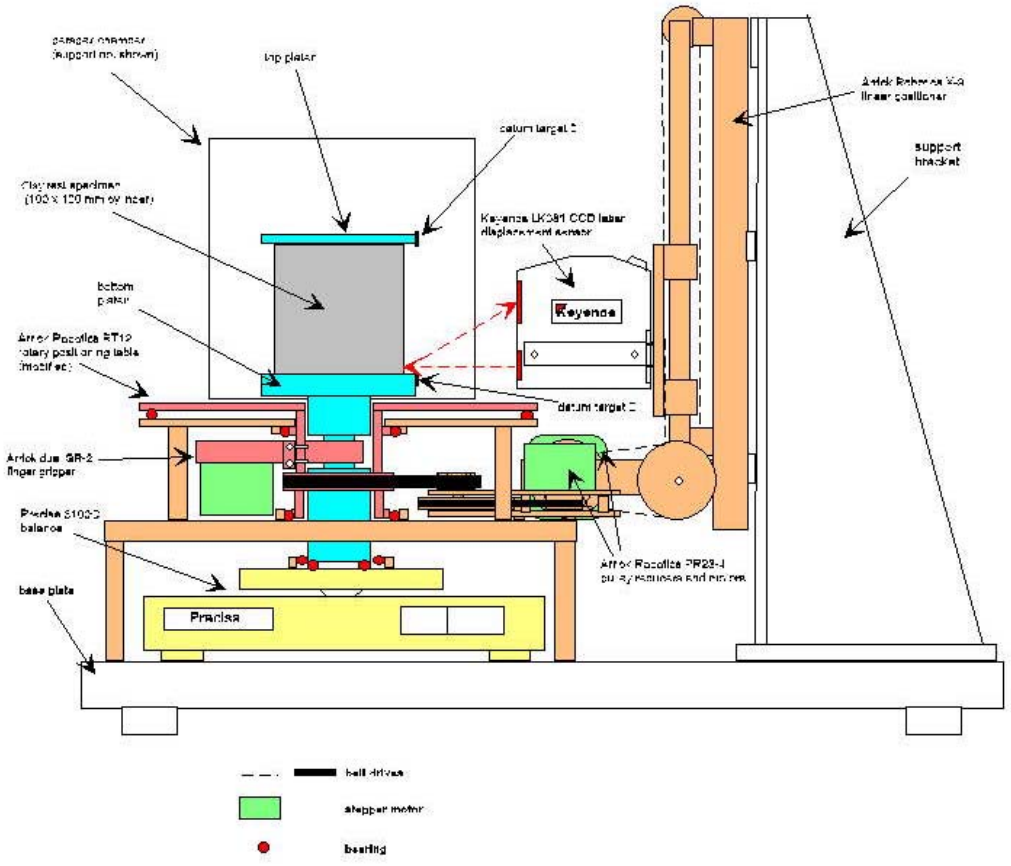

Figure 8 Schematic diagram of original concept of apparatus showing major components (2000)

The overall arrangement of the principal electronic connections for SHRINKiT is shown in Figure 9. The blue lines show control/logging connections and the orange logging only. The item 'DAQ' refers to the analogue to digital data acquisition unit.

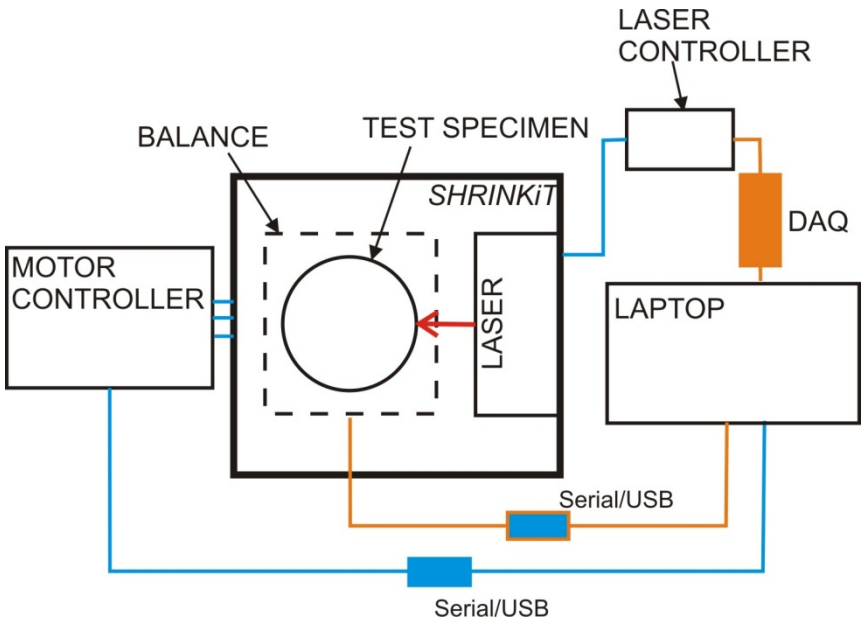

Figure 9 Schematic layout showing SHRINKiT's principal electronic components and connections

5 The SHRINKiT method

5.1 OBJECTIVE

To determine the **shrinkage limit, w_s** of a cylindrical clay soil specimen in an undisturbed, remoulded or compacted state using the SHRINKiT system to determine the shrinkage curve with the graphic construction described in BS1377 (BS1377:1990).

5.2 METHODOLOGY

During a test the specimen's circumferential surface is scanned by the laser, which includes determination of the specimen's height, and the specimen's weight determined before and after each scan and averaged for that scan. The weight is tared before the start of the test to remove the contribution of the support platen assembly (constant, approx. 1.2 kg). Thus during a complete test, thousands of laser range measurements are taken. From these data the software computes a new volume for each scan. This can be done in two ways, selectable in the software, modelling conceptually either 'cheese slice' or a 'stack of discs' (Figure 10). Currently, the 'stack of discs' model is the default and is the only one calibrated for use.

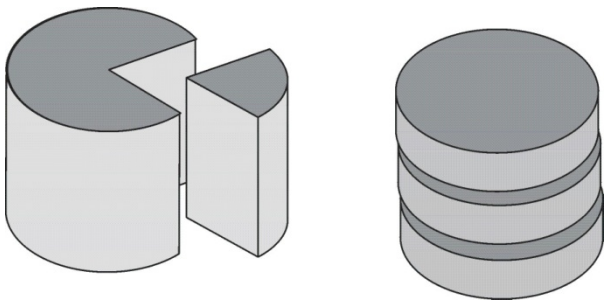

Figure 10 Two conceptual models of volume: 'cheese slice' and 'stack of discs'

5.3 TEST SPECIMEN

Samples of undisturbed, remoulded or compacted clay soil or mudrock may be tested. The test specimen should be a right cylinder with flat and parallel ends so that the initial differences in diameter and height are minimal. Nominally, the height and diameter should be 100 mm or as close as possible. If the ends are not parallel then the specimen may be unstable on the platform or may lean towards or away from the laser and hence may fall outside the permissible range of diameters, in which case the test will be aborted. If the ends are not flat then errors in height determination, and hence volume, will result. It is up to the operator to decide if these errors are acceptable. As a rough guide, initial circumferential height variability should not exceed 5 mm. Best results are achieved (in the case of undisturbed borehole core) by end trimming with a wire saw or thin blade and using some form of right-angle (mitre) jig similar to that commonly used for preparing triaxial test specimens (Figure 11).

The range of specimen sizes which can be accommodated are: Diameter 50 to 110 mm, Height 50 to 140 mm; the former being more critical than the latter due to the range of the Keyence LK-081 laser (nominally 65 to 95 mm from the laser window). The cylindricality of the specimen is also a factor to be considered. Severe non-cylindricality may lead to non-return of the laser beam or failure of the top-edge-recognition algorithm and hence an aborted test (see

section 8.2). Rarely, some soil textures and colours may also result in non-return of the laser beam. This could lead to failure of the test during its first scan. Occasionally problems have been experienced with saturated black or dark grey shales and clays.

The size of the specimen has an effect on the contribution of various heterogeneities; the larger specimens tending to create more problems as described above. However, larger specimens are at the same time more representative of the true engineering behaviour of the soil in-situ, and are preferred for that reason alone; the SHRINKiT specimen being typically 5-10 times larger than the TRL specimen. In selecting a 100 x 100 mm (approx.) specimen the SHRINKiT method seeks to reach a compromise between representativity and testability. *It should be noted that some high density soils (e.g. tills) may give test specimens at this size that are too heavy (>1.9 kg) for the 3.1 kg capacity digital balance and will have to be reduced in height to about 90mm.*

The initial water content of the test specimen is a factor for consideration. Remoulded specimens with high water content may slump when placed on the test pedestal and continue to deform during the early stages of the test. As a general rule, such specimens should be prepared with an initial water content between the liquid limit and the plastic limit.

5.3.1 Preparation of undisturbed test specimens

Undisturbed specimens are prepared in the same way as triaxial specimens, with the exception of the final 1:1 aspect ratio, rather than 2:1. Typically, test specimens are end-cut to length directly from borehole core using a wire saw or thin blade guided by a right-angle mitre-type jig, and then trimmed circumferentially using a wire saw and guide (Figure 11). It is important to ensure that the ends of the specimen are flat and square to the sides using a set square.

Figure 11 Preparation of undisturbed specimen using wire saw and guide (100mm).

Preparation is difficult where highly fissured samples are concerned and an irregular-shaped specimen is often the result. Large holes should be ‘repaired’ with trimmings. Greatest care should be taken in obtaining a clean edge to the specimen ends. An alternative method to using borehole core is to prepare the specimen in the field at outcrop or in a trial pit using a custom plastic or steel bodied core cutter such as a ‘density’ tube or some form of split-tube sampler. This is usually lined with silicone grease to ease the process and help in release of the specimen from the mould. However, any grease residue must be trimmed off after removal of the specimen from the tube in order that drying isn’t inhibited during the test. This type of sample usually has to be extruded, which can itself produce disturbance.

5.3.2 Preparation of remoulded test specimens

Procedures for the preparation of remoulded specimens have varied throughout the project. However, the most satisfactory method to give consistent results for samples with a high clay content was found to be the following:

1. Take sufficient undisturbed (or as received) material, approx. 2.5 kg, and break apart into small lumps.
2. Oven-dry at 40 °C for 48 hours.
3. Powderise to 10µm using a cutting mill.
4. *If large quantities are required (>10 kg) the use of a pug mill to mix with water and de-air may be beneficial at this stage*.
   However, if preparing by hand:-
5. Hand mix approx 1.5 kg powder with de-ionised & de-aired water to a paste at a water content at which the test specimen is capable of self-support (between liquid and plastic limits).
6. Work paste into 100 x 100 mm split mould with a fine nylon gauze liner and end pieces.
7. Vibrate in sieve shaker on low power/amplitude setting to densify and remove air pockets.
8. Separate halves of mould and remove gauze from around specimen.
9. Place specimen on SHRINKiT pedestal.

The final stages (6 – 9) are illustrated in Figure 12.

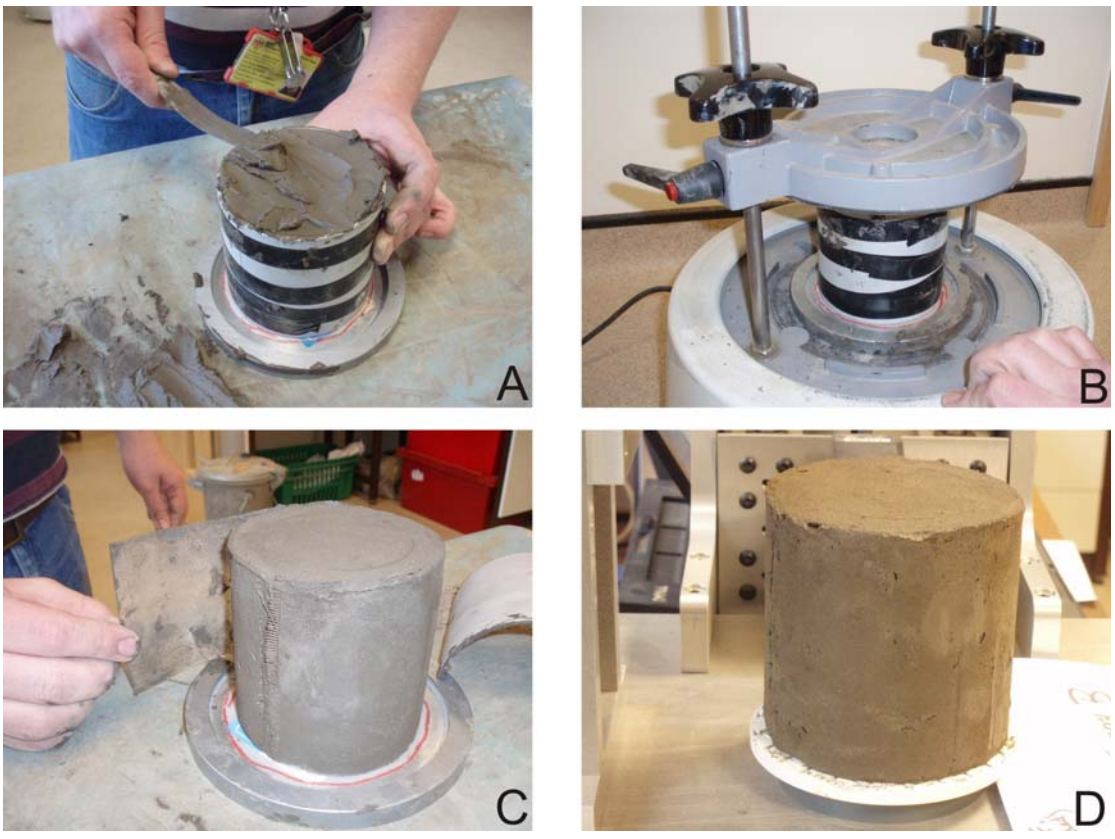

Figure 12 Final stages in the preparation of a remoulded SHRINKiT specimen
A Working soil paste into split mould
B Densification &de-airing using sieve shaker
C Removal of nylon gauze liner
D Specimen mounted on SHRINKiT pedestal

Compacted test specimens may be prepared as for a BS 1377 compaction test (BS1377:1990, parts 1 & 4).

5.4 TEST PROCEDURE

The SHRINKiT shrinkage limit test procedure may be summarised as follows:

- Prepare cylindrical test specimen. Place on test pedestal.
- Select test parameters. Start test.
- Stop test when air-dried shrinkage complete (typically 2 to 5 days). Open data in Excel.
- Remove specimen, oven-dry at 105 ^{o}C, cool in desiccator.
- Replace on test pedestal and test for one scan. Add to test data in Excel.
- Calculate water contents and unit volumes for test. Plot and measure shrinkage limit from BS1377 construction (BS1377:1990).

The test should be carried out in a temperature controlled room or enclosure, preferably at 20 ^{o}C (+/- 1 ^{o}C). It is 'definitive' that all electronic components are switched on at least 2 hours prior to starting the test. This is to allow steady operating temperatures to be reached.

The powering up sequence is as follows:

1. Arrick stepper motor controllers & interface
2. Precisa digital balance
3. Keyence laser
4. Dell laptop

Taring (zeroing) the balance is prompted at the start of the program.

The cylindrical test specimen is placed centrally on the platen. *It should not be moved for the duration of the test until ready for oven drying.* It is not necessary for the specimen to be placed exactly in the central axis of the platen but it should be as close as possible to the centre to keep the specimen within laser range throughout the test.

The SHRINKiT '*.ini*' file is opened and the 'max height to scan' default box value adjusted to be at least 10mm greater than the initial average specimen height. The '*.ini*' file is closed.

The SHRINKiT program itself is started. *The program is currently located in DATA(D:)/VB_Programs*.
A more detailed description of the software is found in section 8.

The opening splash screen appears (Figure 25). *A hand-shake of the 3 stepper motors follows.*

On the opening screen specimen details (number, location and description) can be entered at this point via a button.

A file name can be specified or a default file number accepted.

The rotation increment angle and vertical scan increments are defined; the former must be in the range 3 to 120 degrees and the latter 3 to 30. The rotation increment angle must always be a multiple of 3. A smaller rotation increment angle combined with a larger vertical scan increment will give a higher density of scan points; as an example of the calculation: a 30 degree rotation increment angle with a vertical scan increment of 20 will give (360/30) x 20 = 240 scan points. *The final 10 degrees (i.e. between 350 and 360 degrees) of rotation is automatically removed from all scans in order to prevent mechanical interference with the home switch assembly.* The number of scans per hour is also selected, both for the first 24 hours and thereafter; the purpose being to allow a reduction in the number of scans when shrinkage has slowed. *Care should be taken in selecting these parameters as combining a high number of scans per hour with a high*

density of scan points may not be achievable and may lead each scan not being completed before the next is due In this case the next scan is started immediately after the previous has completed (this is noted on the logging screen). This circumstance is not detected by the current version of the program, but could be incorporated.

A guide to approximate scan durations is shown in Table 5. This will vary with specimen size. The maximum number of scan points selectable per scan is currently 3,510.

Table 5 Guide to scan duration (approx.) for 100x100 mm specimen

Rotation angle increm.	Vertical increment	No. scan points per scan	Duration of scan
30	20	240	4m15s
15	25	600	8m40s
3	25	3000	40m0s

The test is started with the start icon and continues until stopped by the stop icon. During the test various items of data are displayed and updated at each rotation scan on the screen. The progress of the test is entirely automatic and no adjustments or interventions are required, other than to stop it. ***NOTE: the test continues until stopped by the operator.***

In order to produce a 'square' scan point pattern (i.e. equal spacing vertical & horizontal) on the specimen's surface (Figure 13) an example combination would be: rotation increment angle of 6 degrees with a vertical increment of 20, giving a 5 mm (approx.) square pattern on a 100 x 100 mm specimen.

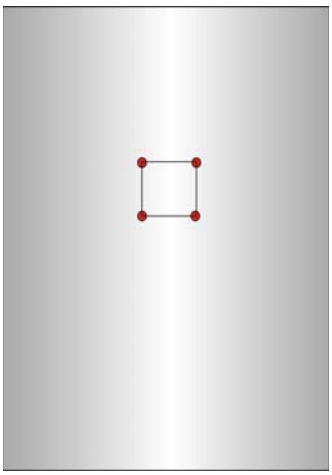

Figure 13 Square laser scan point pattern on specimen's surface

On completion of the test the 3 stepper motors are homed automatically and the data are automatically stored in a folder on the laptop at DATA(D:)/Shrinkit Data. The dataset for each test consists of 4 files with the suffixes: *.vol, .qzr, .ann, .hgt*. Each has a different layout for storing data. Of these the *.vol* file is the most important. The *ann* file shows all the rotational data for each height level of the specimen (i.e. 'stack of discs', Figure 10), the *qzr* file shows all the height data for each rotational increment (i.e. 'cheese slice', Figure 10) and the *vol* file shows a summary of the data for each scan (individual readings not shown). The *.hgt* file shows a summary of height data. The most commonly used is the *vol* file; the relevant volume data are contained in column labelled 'VOL1' with one line per scan. *This file also contains columns labelled 'VOL2' & 'VOL3' which should currently be ignored.* These files can be opened in

Excel (space delimited) using the wizard instructions and the data analysed and plotted. The sample details file, if present, is suffixed *.txt*.

An example of a *.vol* results file is shown in Table 6. Here, each line represents a rotational scan and shows date, time, initial weight, final weight, mean weight and calculated volume.

Table 6 Example of data output file (*.vol* type) Columns: initial & final weights (g) per scan (W1 & W2), average weight (g) (W), calculated volume (mm^3) (VOL 1)

DATE	TIME	W_1	W_2	W	VOL1
		g	g	g	mm^3
28/09/2010	12:27	404.5	404.5	404.5	605438
28/09/2010	12:37	404.5	404.5	404.5	605346
28/09/2010	12:47	404.5	404.5	404.5	605541
28/09/2010	12:57	404.5	404.5	404.5	605514
28/09/2010	13:07	404.5	404.5	404.5	605402
28/09/2010	13:17	404.5	404.5	404.5	605335
28/09/2010	13:27	404.5	404.5	404.5	605141
28/09/2010	13:37	404.5	404.5	404.5	605283
28/09/2010	13:47	404.5	404.5	404.5	605011
28/09/2010	13:57	404.5	404.5	404.5	605168
28/09/2010	14:07	404.5	404.5	404.5	605253

An example of an *.ann* results file is shown in Table 7.

Table 7 Example of data output file (*.ann* type) Columns**:** range (mm) per rotation angle (degr.)

21/07/2010	15:19				
0	60	120	180	240	300
75.1	75.7	76.2	75.5	74.4	74.8
75.1	75.7	76.2	75.5	74.3	74.7
75.1	75.7	76.2	75.4	74.3	74.7
75.1	75.7	76.2	75.4	74.3	74.6
75.1	75.7	76.2	75.4	74.3	74.6
75	75.7	76.2	75.4	74.3	74.6
75	75.7	76.2	75.4	74.2	74.5
75	75.7	76.2	75.4	74.2	74.5
75	75.7	76.2	75.3	74.2	74.5
75	75.7	76.2	75.3	74.2	74.5

An example of a *.qzr* results file is shown in Table 8.

Table 8 Example of data output file (*.qzr* type) Columns**:** rotation angle (degr.), height (mm), range (mm)

13/07/2010	09:40	
60	1	75.5
60	11	75.5
60	22	75.5
60	33	75.5
60	44	75.5
60	55.1	75.6
60	66.1	75.6
60	77.1	75.6
60	88.1	75.6
60	99.1	75
120	1	75.4
120	11	75.4
120	22	75.4
120	33	75.4

An example of an *.hgt* results file is shown in Table 9.

Table 9 Example of data output file *.hgt* type) Columns**:** height (mm)

20/06/2011	14:29		
	1	Height	13.29
	2	Height	13.3
	3	Height	13.3
	4	Height	13.3
	5	Height	13.3
	6	Height	13.3
	7	Height	13.31
	8	Height	13.31
	9	Height	13.31
	10	Height	13.32

The final task for the operator, when air-dried volume change has ceased, is to remove the specimen from SHRINKiT, oven dry at 105 – 110 ^{o}C for 24 hours as per BS1377, cool in a desiccator and replace on SHRINKiT for the final scan. This allows water contents for the whole test to be calculated, as the oven-dried water content is, by definition, equal to zero. Care should be taken to prevent damage to, or loss of material from, the specimen during transfer to and from the oven. Finally, water contents are calculated from the oven-dry weight and average weights per scan during the test as per BS1377, a plot of Water content vs Volume (or Water content vs. Unit volume) is made and the construction to determine **shrinkage limit** carried out, as per BS1377 (BS1377:1990)(refer to).

An ancillary program, *ini*, is also available to make changes to some test and display parameters. The program window (Figure 24) allows changes to the 'laser to platen axis' distance and various default settings featured in the start-up window. When saved, any changes made in the *ini* program are automatically introduced into the SHRINKiT program the next time it runs. *The '.ini' file must be in the same folder as the '.exe' file.*

If necessary, the stepper motors can be controlled and tested independently of the SHRINKiT program using the Arrick Robotics MD2xp program (Figure 26).

The results of a typical test on a specimen of remoulded London Clay Formation are shown in basic format in Figure 14. This plot has a characteristic 'hockey stick' shape with the shrinkage limit approximately midway in the curved section. The normalised plot in Figure 15 is the form in which data should be recorded according to BS1377 (BS1377:1990); that is, water content and unit volume (per 100 g of oven-dried soil). These derived parameters require the oven-dried mass and volume for their calculation. The calculation for unit volume is a follows:

$$U = \left(\frac{V}{m_d}\right) 100$$

Where: U is unit volume (cm^3), V is oven-dried volume (cm^3), and m_d is oven dried weight (g)

The calculation for water content, w (%) is as follows:

$$w = 100 \frac{(m - m_d)}{m_d}$$

Where: m is mass (at water content w) (g), m_d is oven-dried mass (g)

The plots show a broadly two part curve: firstly a straight portion descending from top right representing structural shrinkage of the test specimen. This is followed by a curved transition to a flat line as shrinkage reduces (Figure 15). This ends usually after 2 to 5 days with cessation of air-drying, depending on soil type, specimen state and initial water content. The final point on the curve (shown in red) is the oven dried state. The graphical construction shown in Figure 15 produces, by definition (BS1377), the value for shrinkage limit, which in this case is 19.1 %. The corresponding overall volume decrease, ΔV_{tot} for this sample was 41.5 %.

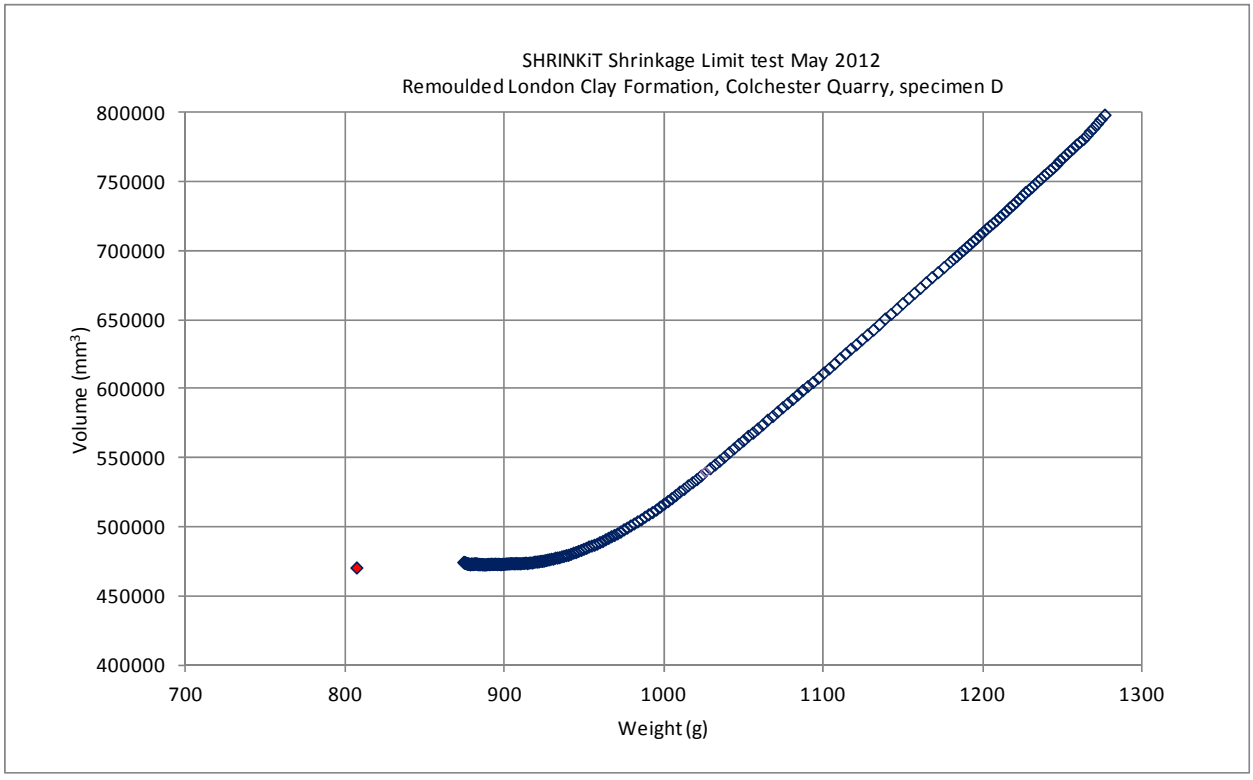

Figure 14 Plot of Weight vs. Volume.

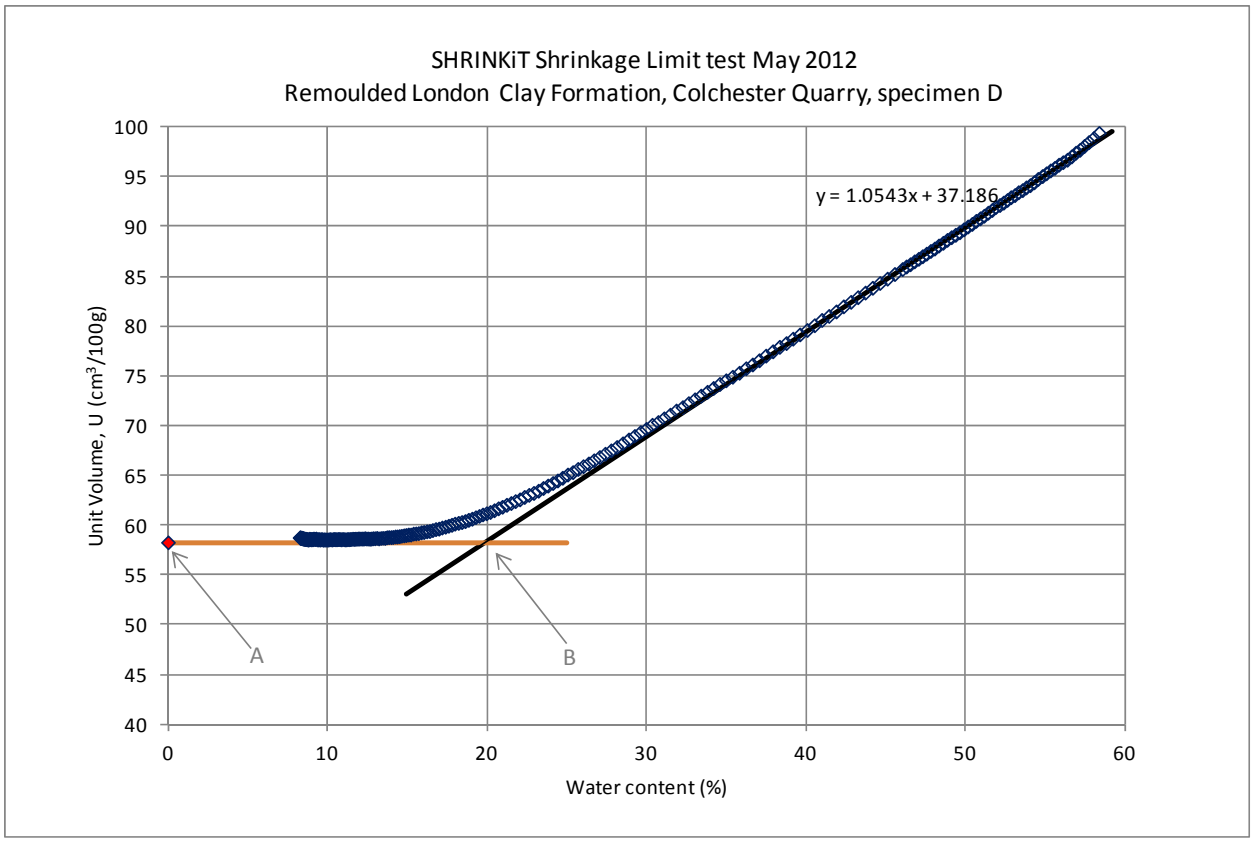

Figure 15 Plot of Water content vs. Unit volume showing construction for determining shrinkage limit.

NOTE: Shrinkage progresses from top right to bottom left. Point A is the oven-dried state from which the orange line is projected horizontally. The black line is a projection of the best-fit (regression equation shown) for the straight initial portion of plot. The intercept of the two lines, Point B, is by definition (BS1377), the shrinkage limit, w_s read from the x-axis (in this case Shrinkage Limit, w_s=19.9 %).

A plot of elapsed time vs. volume for the same test is shown in Figure 16. It will be noted that the test has been carried on well beyond the necessary duration to define the 'residual' section of the plot. This was for experimental reasons and the test could in fact have been completed in 6 days. The overall volume reduction for this specimen was high at 41.5 %.

A plot of elapsed time vs. weight is also shown (Figure 17). This shows a continuous loss of weight almost up to Day 9 despite the fact that volume loss has ended on Day 5. Further weight loss (5 %) has occurred on oven-drying. This behaviour is typical for all samples tested to date.

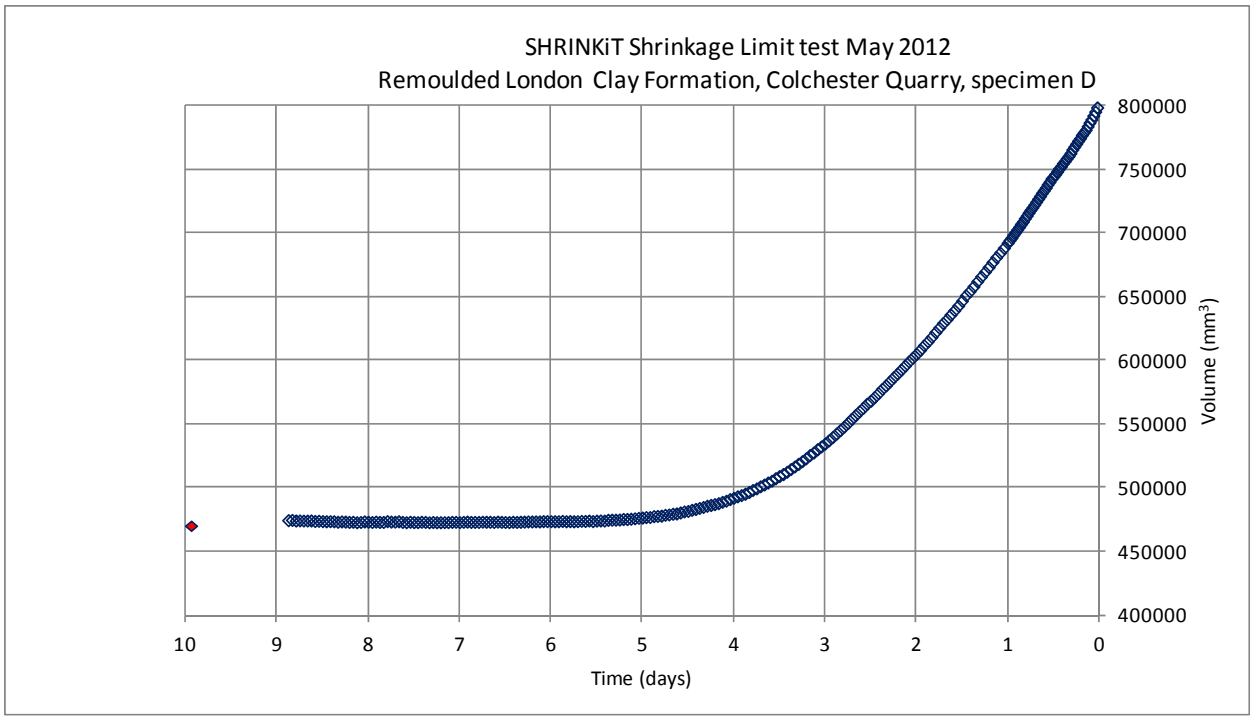

Figure 16 Plot of Elapsed time vs. Volume

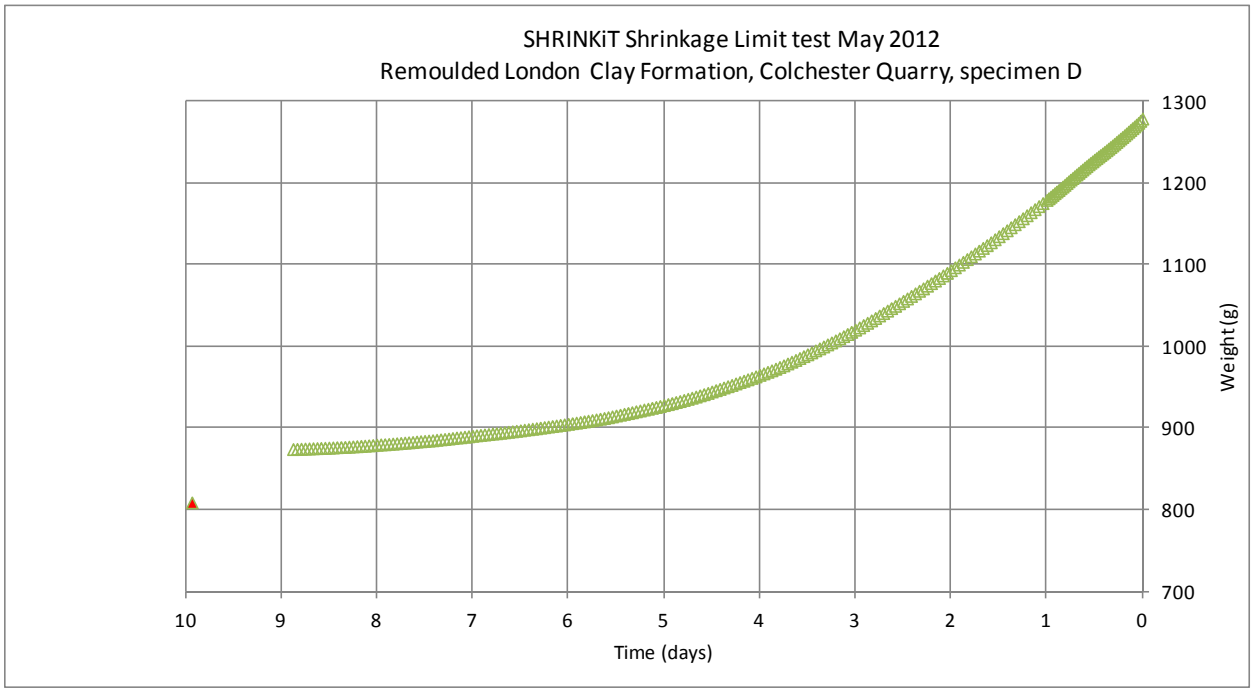

Figure 17 Plot of Elapsed time vs. Weight

The volumetric change V_s of the specimen due to shrinkage from a given water content to the shrinkage limit can be calculated using the following equation:

$$V_s = \frac{w - w_s}{R_s}$$

Where: w is given Water Content of soil (%), w_s is Shrinkage Limit (%) and Shrinkage Ratio, R_s is defined (BS1377:1990) as:

$$R_s = \frac{m_d}{V_d}$$

Where: m_d is oven-dried mass (g), V_d is oven-dried volume (mm^3)

The shrinkage ratio, R_s defined by BS1377 (BS1377:1990), is effectively equal to the dry density, though the two methods described in BS1377 have different units. In fact it may be more logical to deal with shrinkage data in terms of density, though the presence of partial saturation within the specimen may make this confusing.

The overall volume change, ΔV_{tot} (%) of the specimen due to shrinkage may be calculated from:

$$\Delta V_{tot} = \frac{(V_0 - V_d)}{V_0} 100$$

Where: V_o is initial volume (mm^3), V_d is oven-dried volume (mm^3)

An alternative way of presenting the same shrinkage data is as a plot of bulk and dry density. The two values converge, by definition, at the oven dry condition (Figure 18). Also, the maximum point on the bulk density curve should in theory coincide with the shrinkage limit (Garzonio & Sfalanga, 2003). The fact that it doesn't precisely in this case (18.5 % compared with 19.9 %) is probably due to uncertainties inherent in the BS1377 (BS1377:1990) graphical construction and the fact that the bulk density plot has a rather 'flat' top (the peak bulk density achieved during the test of 1.96 Mg/m^3 is first reached at a water content of 21.0 %).

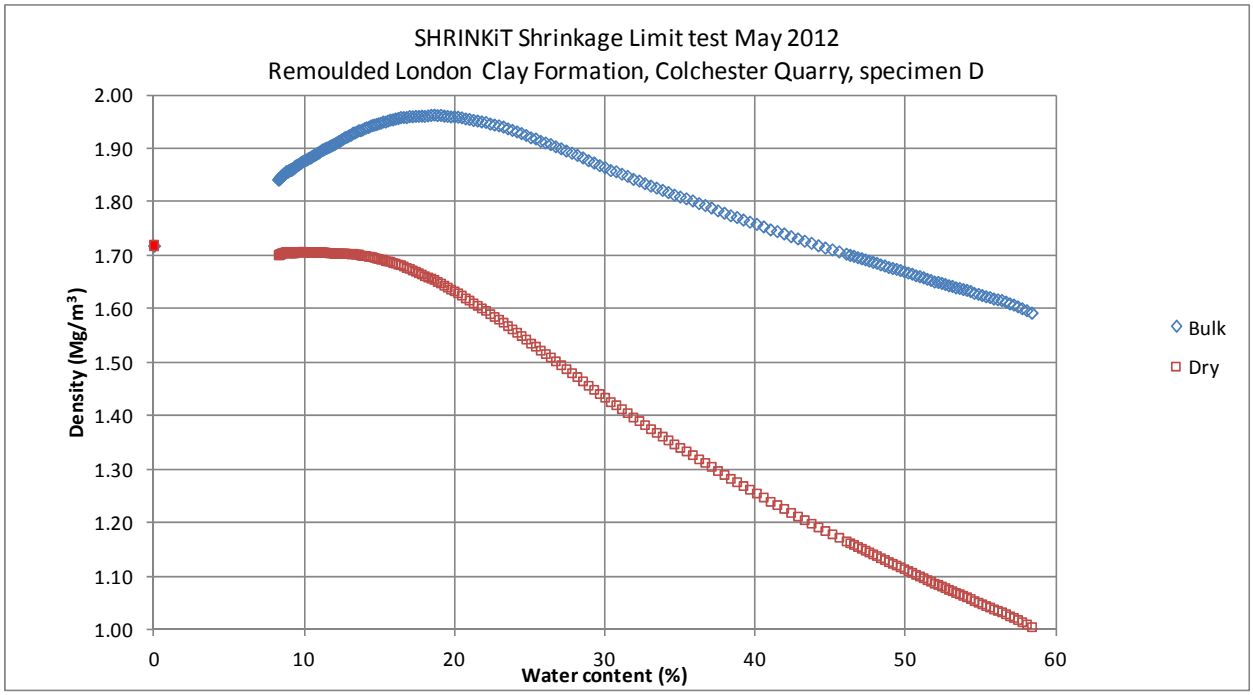

Figure 18 Plot of Bulk and Dry density vs. Water content

The software produces four data file types:

- Raw data: range (laser) readings (*.ann*)
- Raw data: height and range (laser) readings (*.qzr*)
- Summary data: weight readings and calculated volume (*.vol*)
- Summary data: height (*.hgt*)

From the *.vol* summary file, the average weight per scan and the calculated volume (VOL1) are transferred to a spreadsheet in order to produce an X-Y plot of volume vs. water content; the water content being back-calculated from the volume and weight data using the oven-dried weight. Shrinkage limit (w_S) is then derived from the graphical construction (BS1377; 1990), or alternatively using a curve-fitting method (e.g. Braudeau et al., 1999; Cornelis et al., 2006). The amount of shrinkage (total volume change, ΔV), and volumetric strain (ε_v) are also shown.

5.5 EVALUATION

The new test method for the determination of the shrinkage limit of a clay soil using SHRINKiT has the following *advantages* over the two BS1377 'mercury immersion' methods (BS1377). These may be summarised as follows:

1. Hazardous materials, fume cupboard, and protective clothing are not required.
2. The test is automated, with options on amount and rate of data recording.
3. Test specimens may be disposed of in the normal manner.
4. The test specimen is handled only at the start and end of the test. Thus, for the first time, weak, sensitive and metastable samples may be tested.
5. There is no risk of specimen loss or contamination during the test. (This is an important source of error when testing certain soil types in the BS1377 tests).
6. The vertical and horizontal components of shrinkage may be determined separately if required. Particular zones may be examined in greater detail.
7. Large test specimens, e.g. obtained from borehole core, may be used (the TRL method cannot accommodate specimens larger than 45 x 75 mm, and the subsidiary method specimens 44 x 12 mm).
8. The results are likely to be more accurate than those from the BS1377 tests, though this is impossible to prove due to current restrictions in the use of mercury in the laboratory, and even without the restriction would be extremely difficult to prove using the range of natural soils used in the project.

The new method (SHRINKiT) has the following *disadvantages*:

a. The apparatus is expensive and complex compared with both BS1377 apparatus.
b. The density of scan data selected slightly affects the result in some cases.
c. Only one specimen at a time may be tested (current version). The test typically takes several days to complete (but see 2 above).

6 Errors of SHRINKiT and TRL methods

The principal sources of error for SHRINKiT are:

- Deviation from 'true' volume due to scan method and parameters selected.
- Deviation from 'true' volume due to irregularities in specimen surface (& interior)
- Incorrect weight determination due to friction within release mechanism.
- Incorrect positioning due to inaccuracy of movement.

In absolute terms the issue of the accuracy of the scanned-type volume model has yet to be fully explored. The effect on errors of the surface texture, and any irregularities on the specimen's surface, will depend on the scale of these features compared with the density of scan points. A textural characteristic covering the entire specimen surface, for example sand grains, will tend to average out over a scan, whereas a specific irregularity, such as a single crack or hole, will not.

In the case of the TRL mercury immersion method, mercury is capable of entering very narrow cracks and, depending on the surface texture of the aperture, will either exit after immersion or remain lodged, thus introducing both volume and weight errors. In the case of SHRINKiT the laser may penetrate the feature or miss it completely. Of course, in either case the true depth of the feature may not be measured. It could be argued that the 'volume' of a specimen should not include such features, as they do not affect the overall volume and its relationship with the adjacent soil or structure. However, such features may affect the hydrological properties whilst not affecting deformation potential and the calculation of density.

The rate of drying may affect the test result in some cases, in particular as it may influence the development of drying cracks. As yet this has not been verified quantitatively as part of this project. Indications are that airflow, in addition to temperature, is a key factor in determining drying rate. This has been observed while oven-drying using fan-assisted ovens compared with normal ovens. If air-drying is carried out slowly, the occurrence and size of shrinkage cracks may be minimised, although probably not eliminated. Shrinkage cracks in extremely plastic materials, such as bentonite, or clay soils with significant smectite content, may be very large indeed, and constitute a significant proportion of the specimen's surface area. At this extreme it may be possible to map the presence, but not the full extent, of such features successfully with the laser scan.

Severe cracking during shrinkage results in gross deformation and may be accompanied by an *increase* in gross volume rather than a *decrease* (Figure 19). In such circumstances the validity of this test, and indeed any type of shrinkage test, for shrinkage limit determination, is called into question, and such specimens should probably be described as un-testable. Further experimental data are required in order to evaluate these factors. The test plots for this type of soil reveal characteristic small 'steps' in the curve. These match episodes of fissure opening (and closing) observed during the test (refer to section 5.4). This type of curve hinders accurate determination of shrinkage limit by the BS graphical construction method. *It should be noted that such specimens could not have been tested using either of the BS methods.* It has been noted that some clay soils undergo partial crack closure during the later stages of the test.

Figure 19 Image showing severe shrinkage cracks developed during a test on a specimen of 'undisturbed' Gault Formation (P83B) clay from a borehole at Niton (I.O.W.)

In contrast, a specimen of remoulded London Clay Formation showed only minor cracking at a similar stage of the test (Figure 20). This sample (at a smaller specimen size) would have been testable by the TRL mercury immersion method (BS1377:1990).

Figure 20 Image showing minor shrinkage cracks on a specimen of 'remoulded' London Clay Formation from Colchester Quarry, Essex.

The original TRL method was principally intended as a test for remoulded clay soils of 'low' to 'very high' plasticity. Such small specimens tend not to crack severely or break up during the test (this is an important factor with the TRL method as the specimen is handled on many occasions during the test). The same may be said of some undisturbed specimens if dried sufficiently slowly. The BS1377 'definitive' (TRL) method (BS1377: 1990) suggests the use of undisturbed samples, but elsewhere indicates that "undisturbed, remoulded, or compacted samples may be used". However, in practice there are many types of clay soil, which cannot be tested in their undisturbed state using the TRL method. These include some tropical clay soils, loess, laminated clays, silts, and some 'extremely high' plasticity soils. Of course, there may be some soil types which are also unsuitable for SHRINKiT or, for that matter, any other shrinkage limit test. This cannot be determined at present.

The size of the specimen also has an effect on the contribution of various heterogeneities within it; the larger specimens tending to create more problems as described above. However, larger specimens are, at the same time, more representative of the true engineering behaviour of the soil in-situ, and are preferred for that reason alone. Specimens with too high a water content may slump during the early stages of the test leading to errors in volume determination. Specimens with too low a water content may not provide sufficient data to define the shrinkage curve.

In addition to the errors due to the measuring systems, the positioning systems, and combinations of the two, those due to the test specimen itself are significant. From the above, it is clear that difficulty exists in estimating errors in the SHRINKiT test method largely as a result of uncertainties relating to the behaviour of the test specimen itself. In order to measure, and hence attempt to minimise, machine errors a program of calibration against metal cylinders of known volume was undertaken (see section 7).

7 Calibration of SHRINKiT

Calibration procedures have been applied in order to determine the operating parameters of the apparatus, and to allow errors to be estimated. The calibration programme has consisted of the following:

1 Calibration of digital balance (standalone & system)

2 Calibration of laser range finder (standalone & system)

3 Calibration of movement functions (standalone & system)

4 Calibration using calibration pieces of known volume (system)

Items 1 and 2 may be carried out by the manufacturers (primary) or in-house using primary calibrated test pieces. Item 1 is carried out annually by an independent tester. Item 2 is problematic and is not carried out at present. Item 3 examines factors such as drift, stability, backlash etc. associated with motors, drive belts, and bearings. Item 4 is carried out using the whole system in test configuration.

Test cylinders CYL1, CYL3, CYL4 and CYL5 are regular cylinders of different sizes. Cylinder CYL5 is closest to the 'definitive' specimen size for SHRINKiT; i.e. 100 x 100 mm. Random irregularities, broadly imitating those that might be found on a natural soil sample, are machined into a fifth calibration cylinder, CYL 2, in order to investigate the 'sensitivity' of the apparatus to irregularities of different types and scales and the effects of scan data density (Figure 21). The volume of this calibration piece was calculated indirectly by weighing a homogeneous specimen of known density (CYL1). Various problems with the software and hardware during prototype development have been detected and solved using this procedure.

Figure 21 Calibration cylinders (left to right: CYL1, CYL2, CYL3, CYL4 & CYL5)

The properties of the calibration cylinders are shown in Table 10.

Table 10 Aluminium calibration cylinders

Cylinder	Material	Surface	Height (mm)	Outer Diameter (mm)	Outer Volume (mm^3)	Weight (g)
CYL1	Aluminium	Regular	99.9	88.6	615412	431.97
CYL2	Aluminium	Irregular	99.9	88.6	*605735*	404.25
CYL3	Aluminium	Regular	133.2	85.1	757623	867.93
CYL4	Aluminium	Regular	82.1	70.0	315957	393.07
CYL5*	Steel	Regular	100.3	100.1	788857	946.1

*CYL5 represents ideal test specimen dimensions

Table 11 Results of calibration test programme

					Average		%error	%error	Standard Deviation			
Test piece	Name	Software version	Date	No. scans	Weight (g)	Volume (mm^3)	Weight (%)	Volume (%)	Weight (g)	Volume (mm^3)	Gripper springs	Range constant
CYL 1	TestX5	2.3.8	14/07/2010	6	420.03	613271	2.76	0.35			Weak	119.00
CYL 1	TestX6	2.3.8	21/07/2010	10	430.31	591432	0.38	3.90	0.57	151	Strong	119.00
CYL 1	TestX7	2.3.8	22/07/2010	24	429.97	554569	0.46	9.89	0.52	247	Strong	119.00
CYL 1	TestX8	2.3.8	22/07/2010	10	428.96	624686	0.69	-1.51	0.85	1314	Strong	119.00
CYL 1	TestX9	2.3.8	23/07/2010	25	428.92	613073	0.70	0.38	0.51	478	Strong	119.00
CYL 1	TestX10	2.3.9	26/07/2010	25	430.47	612888	0.34	0.41	0.4	529	Strong	119.00
CYL 1	TestX11	2.3.9	28/07/2010	93	427.43	614225	1.04	0.19	4.75	579	Medium	119.00
CYL1	TestX12	2.3.9	17/09/2010	10	427.72	629046	-0.98	-2.22	4.61	411	Medium	119.75
CYL1	TestX14	2.3.11	22/09/2010	35	432.16	616328	0.05	-0.15	0.10	273	Medium	119.75
CYL2	TestX15	2.3.11	22/09/2010	22	404.20	603860	0.01	0.31	0.02	761	Medium	119.75
CYL2	TestX16	2.3.11	27/09/2010	22	404.41	602759	-0.04	0.49	0.08	542	Medium	119.75
CYL2	TestX17	2.3.11	27/09/2010	6	404.23	604640	0.00	0.18			Medium	119.75
CYL2	TestX18	2.3.11	28/09/2010	38	404.5	604875	-0.05	0.14	0.08	953	Medium	119.75
CYL2	TestX19	2.3.11	30/09/2010	10	404.29	603989	-0.01	0.29	0.03	195	Medium	119.75
CYL3	TestX20	2.3.11	26/10/2010	26	867.93	745773	0.00	1.56	0.00	167	Medium	119.75
CYL4	TestX21	2.3.11	27/10/2010	64	393.00	307700	0.02	2.61	0.00	94	Medium	119.75
CYL4	TestX22	2.3.11	04/04/2011	64	393.00	288735	0.00	8.62	0.00	398	Medium	119.75
CYL3	TestX23	2.3.11	05/04/2011	94	867.87	757533	0.01	0.01	0.11	552	Medium	119.75
CYL4	TestX24	2.3.11	06/04/2011	32	393.00	290024	0.02	8.21	0.00	725	Medium	119.75
CYL1	TestX26	2.4.1	17/06/2011	3	431.90	628805	0.01	-2.18			Medium	119.75
CYL4	TestX27	2.4.1	17/06/2011	3	393.00	322015	0.02	-1.92			Medium	119.75
CYL2	TestX28	2.4.1	17/06/2011	3	404.30	619385	-0.01	-2.25			Medium	119.75
CYL3	TestX29	2.4.1	20/06/2011	3	868.00	765102	-0.01	-26.31			Medium	119.75
CYL1	TestX30	2.4.1	21/06/2011	3	431.90	615868	0.01	-0.07			Medium	119.28
CYL2	TestX31	2.4.1	22/06/2011	5	404.30	604414	-0.01	0.22			Medium	119.28
CYL3	TestX32	2.4.1	22/06/2011	10	867.90	748423	0.00	1.21	0.00	72	Medium	119.28
CYL4	TestX33	2.4.1	22/06/2011	3	393.10	313972	-0.01	0.63			Medium	119.28
CYL5	TestX34	2.4.1	23/06/2011	4	946.10	787168	-0.01	0.21			Medium	119.28
CYL5	TestX35	2.4.1	23/06/2011	3	946.10	789318	-0.01	-0.06			Medium	119.35
CYL4	TestX36	2.4.1	23/06/2011	7	393.10	315040	-0.01	0.29			Medium	119.35
CYL3	TestX37	2.4.1	23/06/2011	3	867.90	751160	0.00	0.85			Medium	119.35
CYL2	TestX38	2.4.1	23/06/2011	3	404.30	609070	-0.01	-0.55			Medium	119.35
CYL1	TestX39	2.4.1	24/06/2011	11	432.1	618245	-0.04	-0.46	0.04	89	Medium	119.35
CYL5	TestX40	2.4.1mod	27/06/2011	12	946.10	789487	-0.01	-0.08	0.08	262	Medium	119.35
CYL5	TestX42	2.4.1mod	22/07/2011	66	946.00	789132	0.00	-0.03	0.06	348	Medium	119.35
CYL5	TestX43	2.5.2	21/05/2012	33	945.80	787961	0.02	0.11			Medium	119.35
CYL2	TestX44	2.5.2	22/05/2012	14	404.20	605361	0.01	0.06			Medium	119.35
CYL4	TestX45	2.5.2	22/05/2012	12	393.00	314620	0.02	0.42			Medium	119.35

NOTE: The 'true' volumes of CYL1, CYL3, CYL4 & CYL5 were determined using Mitutoyo digital callipers. The volume of CYL2 was determined using its weight and the density of aluminium calculated from the weight and volume of CYL1. *Calculated density = 2.71 Mg/m^3*

Results of the preliminary calibration test programme are shown in Table 11.

During the calibration exercise various mechanical and software issues were addressed; in particular the operation of the gripper (affecting the weight measurements), the 'true' laser range constant, and use of the laser for edge recognition (determination of specimen height). The gripper springs proved to be a source of problems due to lack of grip (for rotation) in the case of the weaker springs and apparent intermittent incomplete opening of the gripper against the stronger springs (though this turned out later to be due to a software fault). Finally, a 'medium' set of springs was installed and found to operate satisfactorily. The attainment of an even operating temperature for both the digital balance and the laser was found to affect the results and has been accounted for in the test procedure.

The errors reported for calibration cylinders (refer to Table 11) are considered acceptable; i.e. at levels of <0.02 % for weight and <0.5 % for volume.

8 Computer control programme

8.1 GENERAL

The computer programme for SHRINKiT has been developed over the years with some significant changes taking place. Recently, efforts have been devoted to top edge recognition and fault finding. The computer control and logging software for SHRINKiT is described in detail in Gunn (2001) and Roberts (2010). The flow chart for the 'volume' component of the programme is shown in Figure 22. The controlling software for the automatic SHRINKiT test is a Visual Basic V6.0 program running under a Windows XP Pro environment. This program is run as an executable ('.exe') file situated in the Data\Shrinkit\VBProgs\ShrinkitV2.5 directory on a dedicated Dell laptop. The current version is *2.5*, the opening screen for which is shown in Figure 23.

Certain 'constant' parameters for the test system can be changed via an '*ini*' set-up window (Figure 24). This includes, for example, the laser range in millimetres to the turntable axis, the stepper motor and com port assignments and the default settings for the main program window (see below). Normally the parameters in this window will not need to be changed between tests, with the possible exception of the 'max height to scan' parameter.

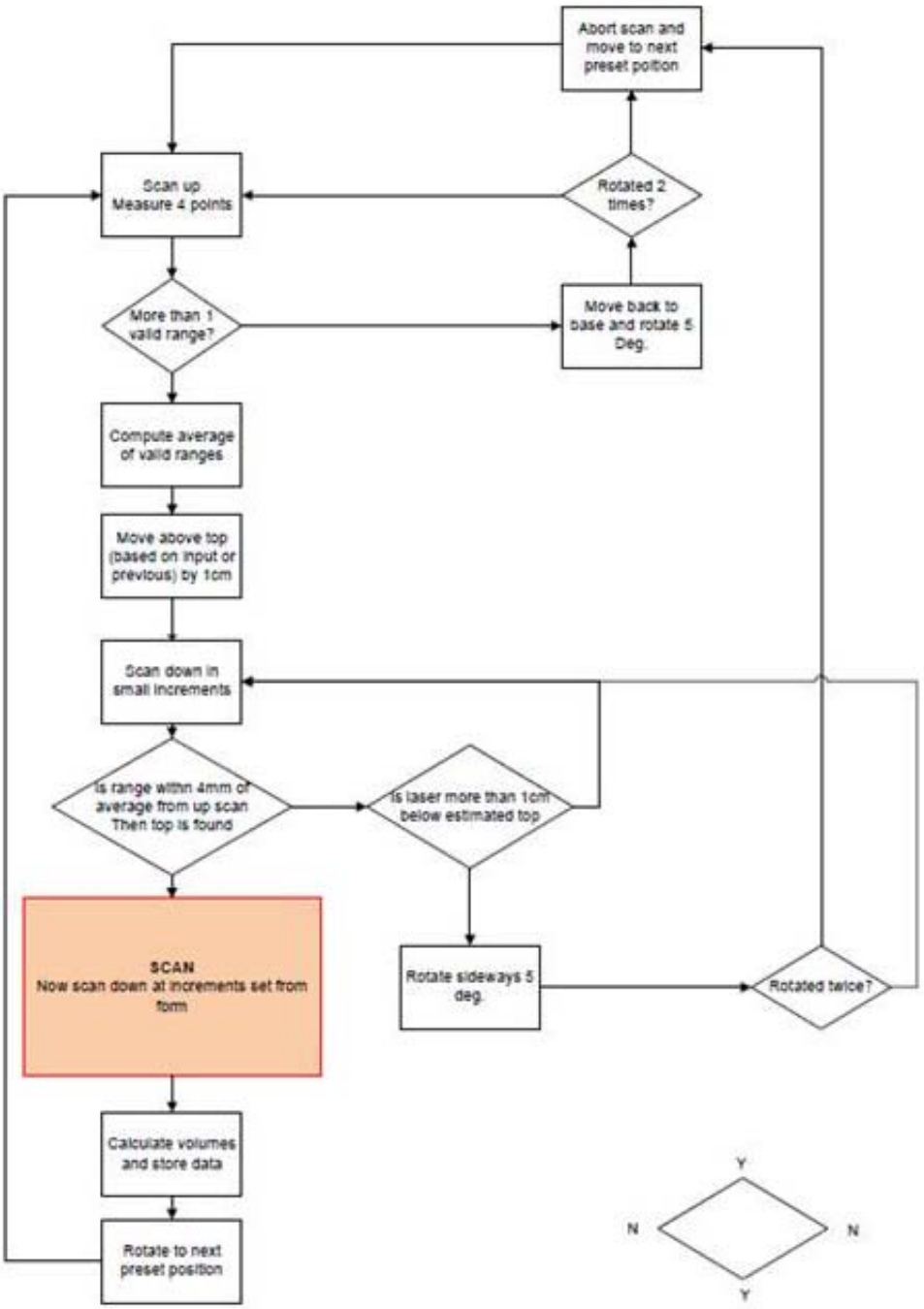

Figure 22 Flow chart for 'volume' component of programme (v. 2.5.2)

The main control program set-up window (Figure 25) contains all the required parameters to carry out the test. The *Rotational Increment* is the azimuthal increment in degrees of the sample's circumference between each vertical transect. The lower the value the more data points gathered and the more detailed the scan. The entry is forced to be a multiple of 3 º and the minimum value accepted is 3 º. It should be noted that all increments greater than 350 º are automatically removed from the routine to prevent collision of the rotating mechanism with the homing switch between 350 and 360 º. The *No. Log Points per Scan* is the number of vertical transect increments as a proportion of the specimen's height. The maximum accepted value is 30 and the minimum is 3. The *1st 24Hrs* (Scans per Hour) is the number of scans to be made each hour. This entry box pertains to the scan rate over the first 24 hours of the test where there is often rapid shrinkage, and thus a need for more frequent readings. This has a maximum value of 6. However it should be noted that selection of a very detailed scan would not allow this number of scans to be carried out

in an hour. The *Rest of Test* (Scans per Hour) is the scan rate that is used for the test after the first 24 hours has elapsed, usually set at a lower rate, say one per hour. In the case where the scan time does not allow the requested scan rate to be met, the apparatus will attempt to scan (and weigh) the specimen continuously with a possibility of data being lost. Fractions can be entered in this box where scan rates are below 1 scan per hour. For example, 1 scan per two hours equates to an entry of 0.5, 1 scan per 3 hrs to 0.33 and 1 scan per 4 hours 0.25, and so on. An example of the main test window is shown in Figure 25.

The results are fed live onto the right hand part of the window. These are updated either at the time of the reading or after each scan has been completed. An indication is also given of the current stage of the test, the clock time of the current and previous scan, and the number of 'missed' scans for that cycle and cumulatively. At the present time no live plotting is available.

A subsidiary window (Figure 26) is available into which specimen details may be entered. This allows name, date, location and description information to be recorded for the test sample. A program outside the SHRINKiT program to test the Arrick stepper motors and the control screen from this is shown in Figure 27. This program (MD2xp, v 2.0.5) allows the motors to be controlled independently of the SHRINKiT software, for example during calibration procedures. The values used in this programme are stepper motor 'steps' rather than degrees of rotation. Generally, 100 steps is equivalent to 90 ^{o} rotation of the motor. However, it should be noted that the use of gearboxes on the turntable and vertical scan assemblies changes this relationship when considering the resulting movement. Both gearboxes have a 4:1 (step-up) ratio.

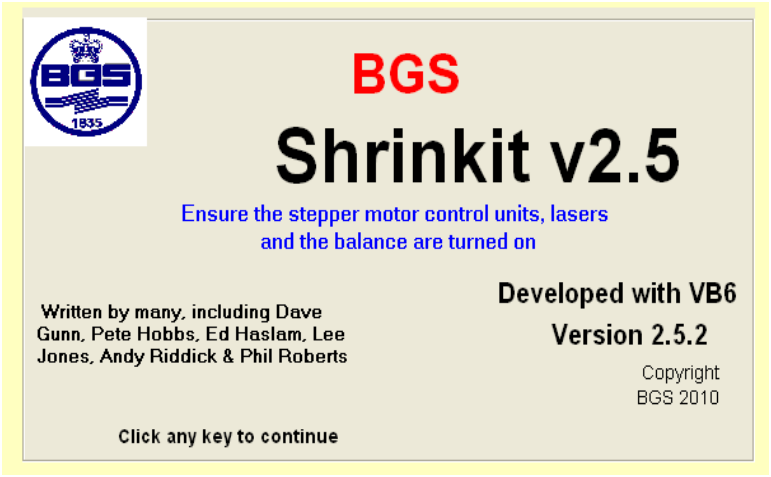

Figure 23 Opening screen for SHRINKiT v.2

Figure 24 Test window for SHRINKiT set-up parameters, '*ini*' file, version 2.5.1 (Roberts, 2010)

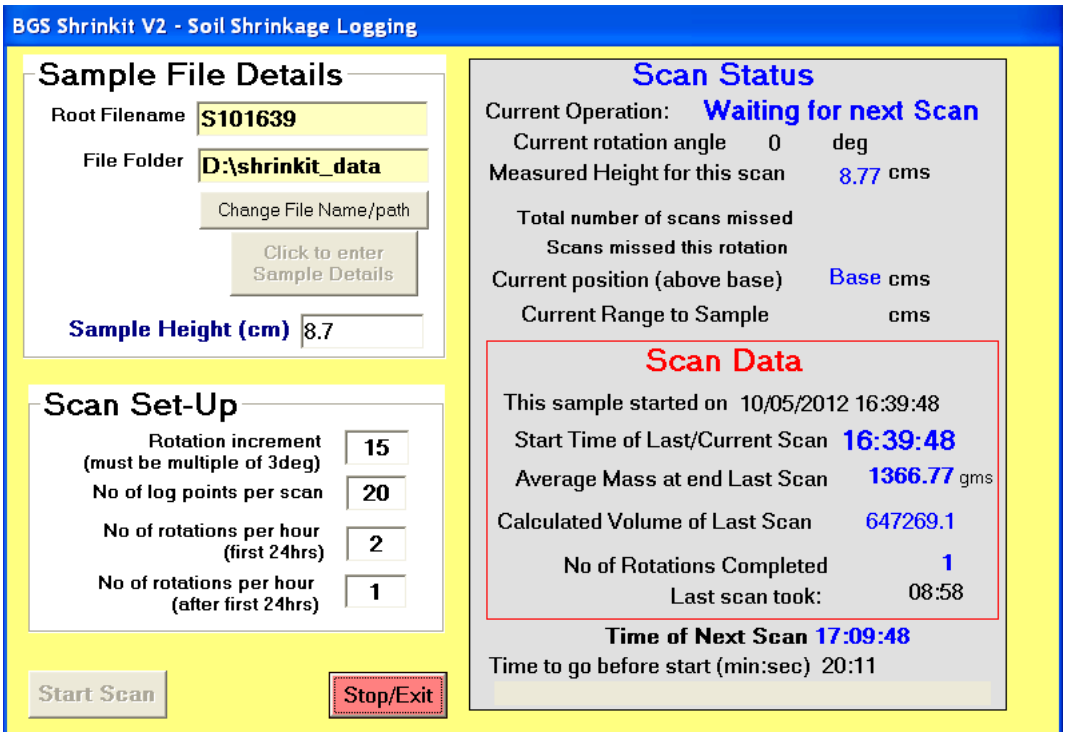

Figure 25 Main test window for SHRINKiT control program, '***exe***' file, version 2.**5.1 (Roberts, 2010)**

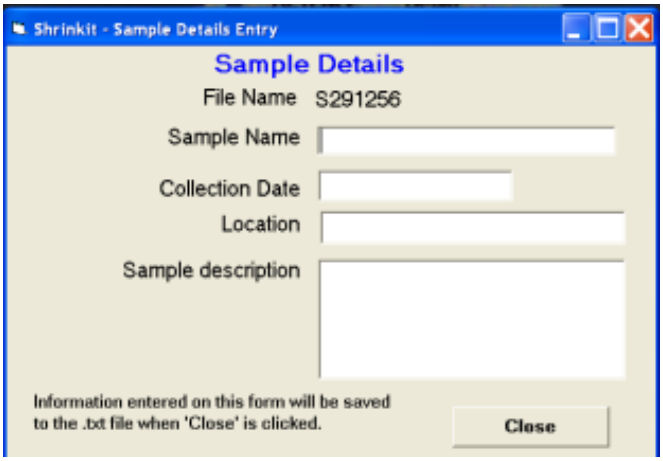

Figure 26 Subsidiary test window for SHRINKiT sample information, '*txt*' file, version 2.5.1 (Roberts, 2010)

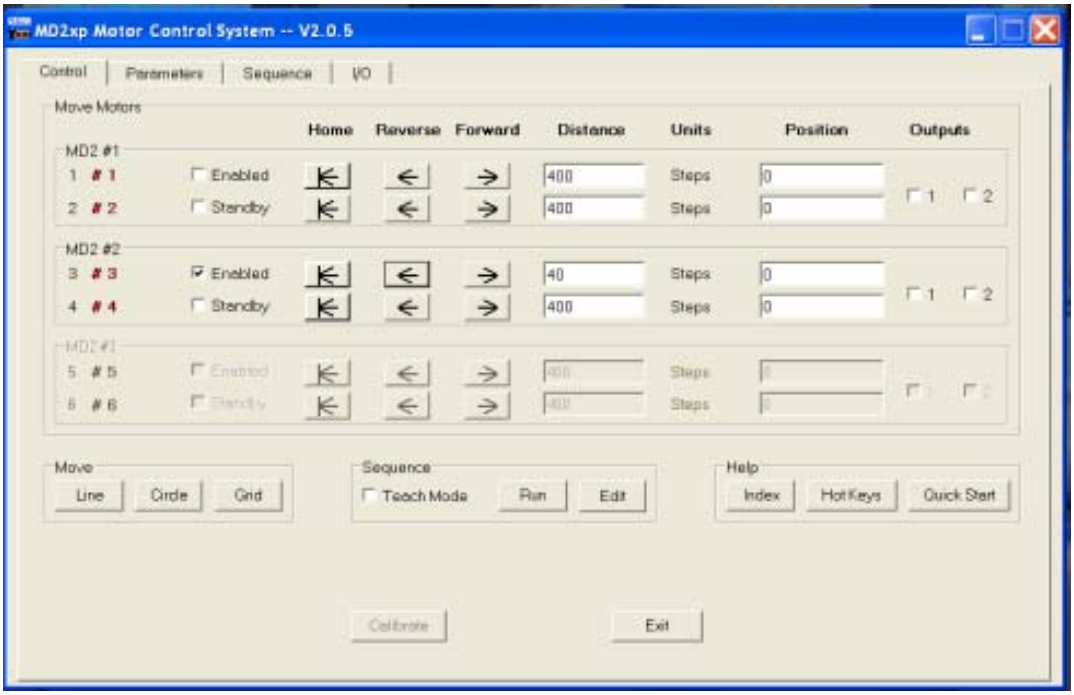

Figure 27 Arrick test window for MD2 stepper motor control outside the SHRINKiT program

The laser aligns with the axis of the platen, A, and remains equidistant from A throughout the test. During a scan, the surface of the specimen is detected at distance B-C, where A-B = D/2 and AC is the 'range constant', currently set at 119.35 mm (Figure 28 and Figure 29). Even with the specimen off-centre, the calculation remains the same.

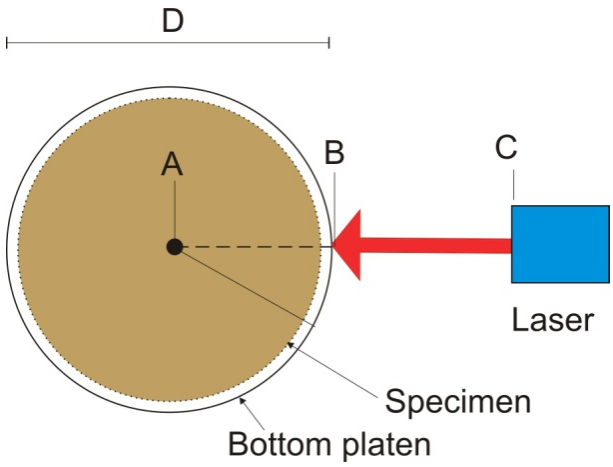

Figure 28 Plan schematic

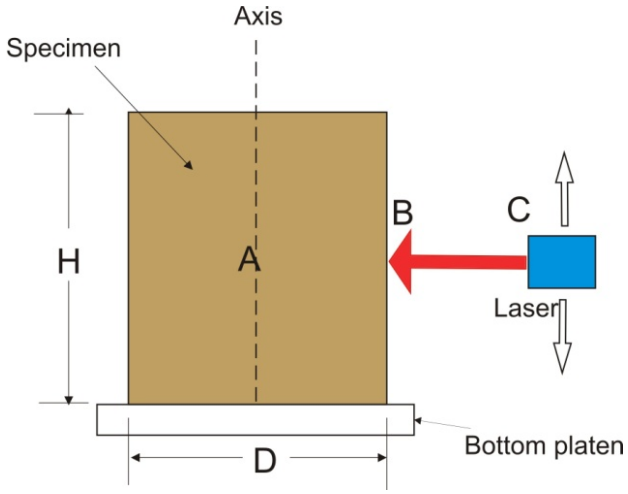

Figure 29 Elevation schematic

A key part of the test is the measurement of the specimen's height. This is achieved on each vertical scan by the laser recognising the top edge of the specimen. It does this by moving from the 'home' position to above the specimen in preset increments, which are subdivisions of the initial height (entered by the operator), to a final upward position above the specimen. The laser then moves downward until a valid range is measured (i.e. within +/- 4 mm of the ranges recorded on the upward travel). This location is then taken to be the 'top' of the specimen (while it is above the top of the specimen the laser is flagging 'invalid' ranges). If the laser fails to find the top, i.e. a 'missing' scan, a sequence of three mitigation moves are available, the final of which is the substitution of the average of the valid ranges for that scan (Figure 22). The test thus continues without aborting, unless the specimen is totally unsuitable and no valid heights have been determined during a complete cycle of scans. Possible reasons for this are:

- Specimen diameter too large or too small (i.e. laser out of range)
- Specimen surface non-reflective (i.e. no valid laser reading within range)
- A technical fault with the laser or motion systems
- An incorrect setting in the *ini* file

The top edge recognition algorithm is discussed in more detail in section 8.2.

8.2 HEIGHT MEASUREMENT USING TOP EDGE RECOGNITION

An important part of the software's algorithm is edge recognition of the top of the specimen in order to calculate the specimen's height and hence changes in height during the test. This is achieved in SHRINKiT v.2 by increasing the functionality of the diameter-measuring laser by also detecting the top edge of the specimen and hence calculating its height. This obviates the need for a second laser. It also provides multiple height determinations around the circumference rather than a single axially aligned measurement. The top edge recognition method is as follows:

- The laser travels upward in increments that are slightly less than one quarter of the initial specimen height. This is to allow the readings to be clear of the bottom and top edges. Range readings are taken at each of these points. If less than 2 valid ranges are measured then the specimen is rotated 5^{o} and the process repeated. If this process has been repeated for more than 2 times, the scan is marked as 'missed' and the sample 'un-rotated' and moved to the next scan point.
- The fifth upward increment is 1 cm above the specimen's top edge (taken as initial height, then updated each scan from the previous scan data). This returns a null reading and prompts slow, downward laser travel until the top of the specimen is detected (within +/- 4 mm of the average value measured on the upward travel).
- Continuing downward at a faster rate, and allowing for a small initial increment, the laser takes the actual test readings of range, and hence diameter, at increments specified by the operator at the start of test.
- If the laser cannot find the specimen top within 1 cm of downward travel from the assumed height, the specimen is rotated 5^{o} and the top edge recognition cycle repeated. This allows for the situation where a vertical fissure is preventing recognition. If the top is now detected a scan is performed and the rotation angle to the next position adjusted appropriately.
- If the laser again cannot find the specimen top within 1 cm of downward travel, the specimen is again rotated 5^{o} and the top edge recognition cycle repeated. If the top is now detected a scan is performed and the rotation angle to the next position adjusted appropriately.
- If the laser again cannot find the specimen top within 1 cm of downward travel, the scan is labelled as 'missed'. The sample is 'un-rotated' back to the original position and the scan marked as 'missed' in the data file. The test continues to the next normal rotation increment.
- At the completion of the scan the successful height determinations are averaged and the value substituted for the 'missing' scan or scans. In addition, and complete scan marked as 'missed' have range values inserted that are calculated from the average of all ranges measured during the rotation. These procedures are to ensure that the data files do not contain missing data.

In relation to top edge recognition, the problems encountered with real specimens are: firstly, that specimens are not perfect cylinders, the geometry of the specimen's top edge may not provide a good laser return and secondly the edge may be curved or contain a fissure or hole, which will prevent the software recognising the top edge on the first pass. To illustrate these factors Figure 30 shows a schematic of an imperfect specimen top edge represented here by a curved surface. If the top edge of the specimen is sharply defined (green line in Figure 30) there is no problem and the top is accurately located. However, if the top is curved or very irregular (orange line in Figure 30) the top is difficult to define accurately.

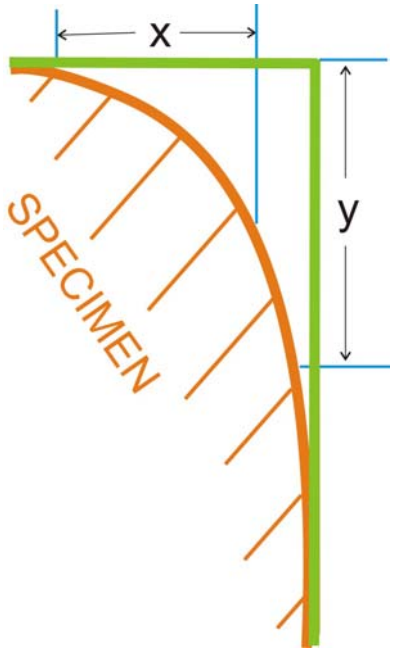

Figure 30 Top edge recognition algorithm applied to an imperfect specimen

It is important for the operator to observe the first scan of any test to make sure there is no failure of height detection at the outset which cannot be recovered in the ways described above. Failure of height measurement is recorded on the live test screen as 'missed height', both for the current scan and cumulatively, and also appended in the database with an asterisk. The only likelihood of failure of top edge detection (and hence of height measurement) in subsequent scans is if a significant piece of the specimen's top edge detaches, or if the reflective properties of the specimen change, during the test. The main test screen shows the number of 'missed height' readings during the most recent scan and also the cumulative number of 'missed heights'. This is a guide as to whether or not a problem exists, or is developing, with the specimen.

In practice, it is possible for the top edge recognition algorithm to fail if a poorly prepared test specimen is used. If problems develop during the test, for example due to severe fissuring or disintegration of the specimen, then it may be necessary to abort the test. Frequent instances of 'missed heights' will result in erroneous volume readings.

9 Future developments

It is anticipated that calibration, evaluation and experimentation with SHRINKiT will allow refinement and simplification of both the hardware and software. It is planned to introduce the following features:

- A digital camera with which the progress of shrinkage can be followed by recording images of crack development and colour change.
- A computer-controlled environmental chamber surrounding the test specimen, within which the specimen may be dried, or possibly wetted, at varying rates. This could be achieved by a warm air fan and a humidifier, respectively. The influence of drying rate on the measured shrinkage limit could thus be investigated, and possibly from this an 'accelerated' test developed, thus increasing the throughput of specimens; for example, by introducing dry air to an enclosure. Scans of shrinkage and swelling, and any associated hysteresis effects, could also be investigated in an attempt to duplicate natural climatic processes and examine their effects on foundation performance.

- A version 3 could incorporate design changes resulting in reduced size, weight and cost of the apparatus. The introduction of a multiple specimen carrousel would also allow greater sample throughput. A version 3 would probably also include unitary black-box control & logging electronics rather than the present off-the-shelf systems. This would be advantageous prior to any attempt to market it as a saleable product.

In addition, further refinement of the software is desirable. This may include the following:

- A preliminary 'diagnostic' scan to determine if there are any problems with the test specimen.
- Live graphical output so that the progress of shrinkage can be assessed.
- Incorporation of the final oven-dried weight into the 'live' calculations.
- Calculation of time taken for each rotation during initial entry of parameters to avoid overruns into the time point for the next.
- Further development of software may require changes in the way the programming language Visual Basic (VB 6.0) is used, as this is no longer officially supported under the current version of Microsoft Windows (V7). A change to the current version of Visual Basic (VB .NET) would require a substantial re-writing of code. However, Microsoft recommend running VB 6.0 under a 'Virtual Machine' within Windows 7, and this may be possible but not yet tested for this application. There are also recognised 'work-arounds' to allow the successful installation and running of VB 6.0 under Windows 7.

As part of future project research work it will be possible to link SHRINKiT test results to suction (extractor plate) test results, as described in section 2.2, using water content as the common parameter. Hence, it should be possible to infer shrinkage from suction measurements for a given soil type and condition. Also, investigation as to the minimum (or optimum) scan density for a given soil type or condition will be carried out.

10 Conclusions

The SHRINKiT (v.2) apparatus and method developed at the British Geological Survey's geotechnical laboratories have been designed using reliable and accurate scientific sensors to measure the changing water content and volume of a clay soil specimen and hence derive the 3rd Atterberg parameter Shrinkage Limit, w_s using the graphical construction in BS1377 (BS1377:1990). The apparatus has been constructed at the BGS Workshops. The equipment is fully automated, apart from final oven-drying, and the test is controlled and data logged automatically. The traditional methods currently standardised worldwide use large quantities of mercury, in some parts of the world without adequate control measures, and have been deemed unsafe in many countries. The SHRINKiT project has received support in its latter stages from NERC's Innovations A fund for new technology. In particular, this has enabled the software to be refined, de-bugged and tested.

Whilst it has not been possible to directly compare the SHRINKiT (v.2) results with results from the 'definitive' BS1377 method (BS1377:1990), due to restrictions in the use of mercury, several comparative tests using the version 1 (manual) apparatus were carried out on a variety of clay soils early in the project before restrictions came into force (Hobbs & Jones, 2006). These showed close agreement and satisfied the project team that the automated version 2 with its similar method but greatly enhanced measurement accuracy would provide equivalent correlations and exceed the performance of version 1. The development of a commercially viable product (v.3) will be dependent on the further availability of funds, on continuation of the SHRINKiT project at BGS and on the adoption of a commercial partner. Efforts to achieve these goals are ongoing at the time of writing.

Despite its long gestation the automated (v. 2) SHRINKiT became operational in September, 2010 and a program of calibration and trials was carried out during 2011/12. In terms of marketing opportunities there are broadly two options:

1. BGS could provide a shrinkage limit testing service using SHRINKiT at BGS, in particular to the civil engineering and building industries.
2. BGS could manufacture or licence SHRINKiT for sale to commercial and academic laboratories. This would require a further substantial investment of time and money in order to make it cost-effective and marketable, though this should not be discounted at this juncture. An alternative programming medium to Visual Basic (VB) would probably be required.

Of these options the first is closer to realisation than the second, as it would not require a further large speculative investment and design input. However, it may require construction of one or more additional apparatus in the event that commercial testing becomes a reality. This would cost an estimated £10 k per apparatus (at time of writing), consisting mainly of staff time and machine shop time/materials (either within BGS or external). The sensors (laser & balance) for one additional apparatus are currently available though further purchase of stepper motor controllers and A/D converters would be required (approx. £1 k at time of writing).

Further assessment of the variety of clay soil types and specimen sizes, shapes and moisture condition that can be tested successfully using SHRINKiT is required. This knowledge will develop with experience and cannot be fully achieved at present. The ability to test soil types and states that have previously been un-testable has posed new questions about the precise nature of shrinkage; for example, clays subject to fissuring which increase in volume whilst simultaneously shrinking due to the development of voids. Whilst on occasion making derivation of the shrinkage limit difficult, these new considerations have added to the understanding of shrinkage in 'real' materials as found on site which, more often than not, are neither fully remoulded nor perfectly undisturbed. Such properties have implications for the understanding of subsidence damage and foundation behaviour generally.

There is much scope for research into the shrinkage behaviour of natural soils for geotechnical applications. The SHRINKiT apparatus can play an important part in this as it has been designed with geotechnics in mind. Notwithstanding, applications for SHRINKiT in the fields of agriculture, soil science and industrial clays may also be cultivated.

NOTE:
The results of the 2008 to 2012 SHRINKiT testing programme are described in a separate BGS report (Hobbs et al., 2012).

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