A new apparatus for determining the shrinkage limit of clay soils

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ABSTRACT

A new apparatus for the determination of shrinkage limit is described. Two versions have been produced: a manually operated prototype 'version1' followed by an automated version named SHRINKiT. Test results using the former for British and overseas clay soils are described and comparisons made with the BS preferred method. A further set of test results is described for SHRINKiT. However, it was not possible to compare these with the BS1377 method due to the introduction of a ban on the use of mercury in the British Geological Survey's geotechnical laboratories. The new method is set in the context of the huge cost of shrink/swell related subsidence damage in Britain and the relative disuse of both BS1377 methods for shrinkage limit due to reasons of safety. The shrinkage behaviour of different soils types and sample states is discussed, in addition to the advantages and disadvantages of the new method.

INTRODUCTION

Clay soils constitute a familiar hazard to engineering construction and house building in terms of their ability to shrink and swell; that is, to change volume with a change in effective stress, usually caused by alteration of water content produced by seasonal climatic variations (Anon, 1993). The study described in this paper has examined some of the geotechnical aspects of shrinkage, and in particular has developed a new test apparatus for the important, but neglected, Atterberg limit: the *shrinkage limit*. A range of clay soils has been tested using both version 1 and SHRINKiT in order to prove the concept. The other two Atterberg limits have been included so that correlations, both familiar and new, can be examined.

Annual insurance costs for subsidence attributed to swell/shrink in Britain are of the order of £300-600m (Jones, 2004). As climate trends appear to be resulting in greater seasonal water contrasts for much of the country (Hulme *et al*., 2002), the current trend for increasing claims can be expected to continue. There has also been debate about the precise role of trees and impermeable surfacing in the clay shrink/swell phenomenon (Skempton, 1954; Cheney, 1986; Randrup *et al*., 2001; Mathheck *et al*., 2003; Jones *et al*., 2006).

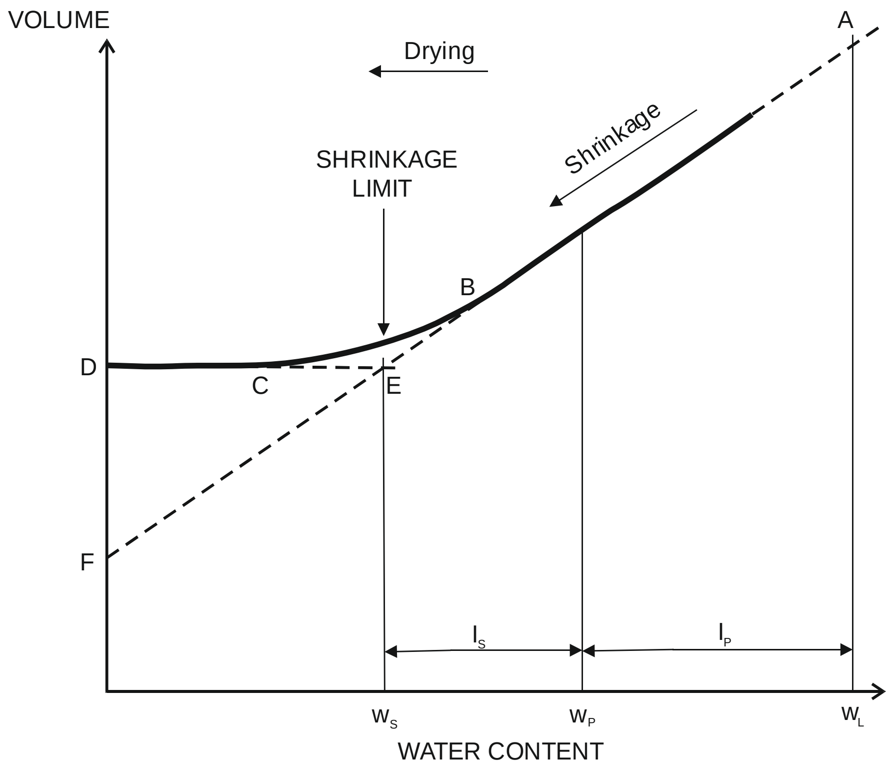

Figure 1 Schematic plot of water content vs. volume showing Atterberg Limits
Key: w_S=Shrinkage limit, w_P=Plastic limit, w_L=Liquid limit, I_S=Shrinkage index, I_P=Plasticity index

The shrinkage limit was one of seven state limits conceived in 1911 by Albert Atterberg and termed “Krympning gräns” in Swedish and “Die Schwindungsgrenze” in German (Atterberg, 1911a, 1911b; Casagrande, 1948; Skempton, 1985; Sridharan & Prakash, 1998b; Haigh *et al.*, 2013). The shrinkage limit (w_s) is conceptually the boundary between ‘solid’ and ‘semi solid’ consistency, and is defined as the water content below which no further volume reduction takes place on drying (Fig. 1). Referring to Fig. 1 the steady shrinkage from A to B is where volume reduction matches water loss, and is described as the ‘basic’ stage by Boivin *et al*. (2006b) or ‘normal’ stage by Sridharan & Prakash (1998b). The gradient of the line AB is the initial degree of saturation and, if volume change is expressed as a percentage of dry volume, equals the shrinkage ratio, R_S. The shrinkage stage from B to C (alternatively E to C) is described as ‘residual’ with point E defining the shrinkage limit (BS1377:1990). Point D is the oven-dried state (105^{o}C) and between C and D there is no volume reduction. However, in practice there may be small volume decreases here. Point B is usually referred to as the air-entry point (Haigh *et al.*, 2013) and represents the water content at which water loss outstrips volume reduction and saturation starts to reduce dramatically. The projection of the line AB to F represents the volume of solids (Reeves et al., 2006). The shrinkage limit is therefore the water content value at the intersection of construction lines DE and AE, which also coincides with the point of maximum bulk density. The specimen’s initial water content determines the start point of the test curve. In the case of remoulded specimens and soil mixtures (Sridharan & Prakash, 2000) this is usually midway between liquid and plastic limits. At higher water contents the specimen is liable to slump. In the case of natural ‘undisturbed’ specimens the initial water content is often closer to the plastic limit.

For most British clay soils and mudrocks the values of shrinkage limit lie in the range

12 to 25 % whilst for some tropical and bentonitic clay soils values lie between 30 and 50 % (Hobbs *et al*. 2012). Whilst much use is made worldwide of inferred swelling and shrinkage behaviour obtained *indirectly* from standard soil 'index' test data such as plasticity, density, and water content, few data derived from *direct* shrink/swell measurement are available, at least in British geotechnical databases. This is partly because the familiar 'index' tests are more explicit and accepted worldwide and partly because direct shrinkage tests are difficult to perform, particularly with *undisturbed* weak, fissured, or sensitive soils. Soil structure, fabric, and water content contribute to test difficulties and tend to make correlations between field shrinkage and liquid and plastic limit data (remoulded state) questionable.

At present, the two British Standard methods for measuring shrinkage limit directly employ Archimedes principle applied to a mercury bath (BS 1377, BSI, 1990). The 'definitive' method employs a special mercury cell with built-in micrometer originally developed by the Transport Research Laboratory, TRL (Road Research Laboratory, 1952; Ackroyd, 1969). At BGS this test used to be carried out in a fume cupboard, with a mercury recovery kit to hand. The 'subsidiary' method, 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) also uses mercury immersion and the same graphical construction as the 'definitive' method to obtain the shrinkage limit and has been used worldwide.

Both British Standard methods BS 1377:1990 (BSI, 1990) are compromised because mercury presents a significant health hazard as liquid and vapour, and is banned in many soils laboratories. Consequently, alternative methods have been sought. Travelling microscopes have been used for measuring 1-D swelling of soil in the laboratory (for example, Parcevaux, 1980) and may also have been used to measure shrinkage on an ad-hoc basis elsewhere. In the early stages of the project a laboratory apparatus was built which incorporated a travelling microscope, a laser range-finder, and a digital balance, in order to measure 3-D shrinkage and hence determine shrinkage limit and other parameters, without the use of hazardous substances or contact with the test specimen during air drying. This prototype apparatus, referred to as 'version 1', was manually operated and was used to compare results obtained with the BS1377 (TRL) BS 1377:1990 (BSI:1990) apparatus (Hobbs *et al*., 2010).

Figure 2 British Geological Survey's automated shrinkage limit test apparatus, SHRINKiT

Subsequently, a fully automated apparatus referred to as 'SHRINKiT' (Fig. 2), was designed, constructed and used to carry out a shrinkage limit test programme on a variety of British soil types (Hobbs et al., 2010; Hobbs et al., 2012). It was not possible to make direct comparisons between this method and the BS1377 methods as use of the latter had by this time been banned in BGS's geotechnical laboratories.

CLAY SHRINKAGE RESEARCH IN THE LABORATORY

Considerable research in the fields of soil physics, agriculture, sports surfacing and more recently unsaturated soil mechanics, has been carried out on the subject of soil shrinkage. Soil physics has, in the past, favoured the use of flexible resin coating of natural soil aggregates or 'clods' to measure shrinkage in the laboratory, e.g. the 'paraffin' method (Parker *et al*, 1977; Reeve *et al*., 1980). However, a 'core' method (Berndt & Coughlan, 1976) and a 'balloon' method (Tariq & Durnford, 1993) have also been widely used. A frame-mounted transducer (LVDT) method was also described by Boivin (2007) and Williams & Sibley (1992). More recently, laser scanners have been used to measure the volume of clod-type soil specimens either to determine the shrinkage curve (Sander & Gerke, 2007) or simply bulk density (Rossi *et al*., 2008). Sridharan & Prakash (2009) have also reconsidered the wax method for shrinkage limit determination.

Much attention has been focused on models to predict and match so-called 'soil shrinkage characteristic curves' (SSCC or SSC) (Bronswijk, 1990; Groenevelt & Grant, 2001; Cornelis *et al*., 2006), 'soil shrinkage curves' (ShC) (Boivin *et al*, 2006b), 'volumetric shrinkage curves' (VSC) (Mbonimpa et al. (2005) and the 'reference shrinkage curves' (Chertkov, 2007a) and in particular on its quantification and use in determining soil structure (Braudeau *et al*., 1999; Crescimanno & Provenzano, 1999) and soil compaction (Boivin *et al*., 2006a). The SSCC and ShC have been attempts to model families of sigmoidal shrinkage curves by sub-dividing the curves into seven recognisable zones separated by transition points. These zones are described as either linear or curvilinear. The 'reference shrinkage curve' (Chertkov, 2007a) is a theoretical curve derived from eight parameters, designed to remove the contribution from crack volume, and seeks to de-couple real soil shrinkage behaviour from that of a pure clay and hence distinguish the contribution of cracking. In geotechnical terminology this could be analogous to 'undisturbed' and 'remoulded' states, but where the remoulded sample had been ground to clay size. As part of this concept Chertkov (2007a,b) described the 'critical clay content', defined as the ratio of clay solids to the total volume of solids.

The soil water retention curve (WRC) (Gould *et al*., 2011), for example as produced from a suction (extractor plate) test or tensiometer test (Ridley & Burland, 1993), is mathematically similar to the soil shrinkage curve but, in the case of clay-rich soils, may itself include an element of shrinkage (Mbonimpa *et al*., 2005). Attempts to fit the soil water retention curve (WRC) and ShC to the same equations were made by Boivin *et al* (2006b). In practice it should be possible for an experimental suction test curve to be mapped to a corresponding shrinkage curve from the same sample. Thus a 3D critical state plot of shrinkage could be constructed, at least for a remoulded sample, showing water content vs. volume vs. stress; the stress being negative.

The development of a new apparatus was also reported. This was designed to test several small specimens mounted in a carrousel device and using separate laser range finders to determine diameter and height (Braudeau et al., 1999). This apparatus was developed independently at around the same time as SHRINKiT and is similar in principle. However, it uses much smaller specimens and, though a quicker test, is probably unsuitable for undisturbed specimens. Shrinkage test methodologies and models, in the field of soil science, were compared in Cornelis *et al*. (2006). They concluded that the 'balloon' method was superior to the 'core' and 'paraffin' methods, and of the curve modelling methods, the SSCC of Groenevelt & Grant (Groenevelt & Grant, 2001) was the simplest and most elegant.

Shrinkage research on particular soil types is less common than that dealing with theoretical aspects, or utilising soil pastes rather than undisturbed specimens. For this reason it is unlikely that soil physics or agronomic methods or analyses, such as those described above, would find favour with geotechnical practitioners. A possible exception to this might be the balloon method (Tariq & Durnford, 1993). However, most geotechnical testing is based around cylindrical or discoid specimens of undisturbed, remoulded or compacted material, such as might be obtained by drilling, rather than irregular 'clods'. The following deals with a proposed geotechnical approach to shrinkage measurement which follows logically from the BS methods BS1377:1990 (BSI, 1990), but which provides additional data of use in characterising the engineering behaviour of a clay soil.

THE SHRINKiT APPARATUS

The apparatus (Fig. 2) described in Hobbs et al. (2010) has five active components:

a) A laser rangefinder (to measure diameter and height).
b) A digital balance (to measure weight).
c) Motorised rotating platform.
d) Motorised elevation gantry.
e) Motorised gripper to allow rotation.

The apparatus is designed to take a100 x 100 mm cylindrical test specimen. However, the range of sizes that can be accommodated is 50 to 110 mm (diameter) and 50 to 140 mm (height), dependent on net shrinkage during the test. The test typically takes between 3 and 5 days, depending on soil type, specimen state and environmental conditions, during which the specimen is scanned twice hourly for the first 24 hours and hourly thereafter. At the conclusion of air-drying, the specimen is removed from the apparatus, oven dried at 105^{o}C and returned to the apparatus for its final scan. Thus, the specimen is only handled twice during the test. Volume measurements are calibrated against metal cylinders of varying size and shape with known volume.

The TRL apparatus recommended by BS1377:1990 (BSI, 1990) is difficult to use particularly with fissured, voided, silty, weak, sensitive or highly plastic clays in an undisturbed state. Over-consolidated, tropical and loessic soils usually fall into this category. Fewer problems are experienced when testing remoulded or normally consolidated undisturbed soils. However, cracks which develop during the test tend to be entered by tiny globules of mercury, a proportion of which remain within the specimen during drying, particularly where surfaces are rough or silty. This results in combined volumetric and weighing errors of up to 5% and allows mercury vapour into the atmosphere. Larger globules are dislodged by tapping the specimen on removal from the cell whereas tiny globules are not. Additionally, fragments of soil may detach from the specimen and fall into the mercury. This introduces further volumetric and weighing errors. The BS1377:1990 (BSI, 1990) subsidiary method (equivalent to the ASTM method) uses a small disc of remoulded soil, is even less well suited to undisturbed soil specimens and is even less safe, as the mercury is open to atmosphere and prone to spillage. Existing test methods using mercury should be carried out in a fume cupboard. To the authors' knowledge this is often not the case in some countries. In addition, the disposal of mercury contaminated specimens requires special procedures.

Neither BS method requires the volumetric strain (net shrinkage) of the specimen to be recorded, though a plot of volume per 100g of dry soil, U vs. water content is specified. The volumetric strain is dependent on initial degree of saturation. The test specimen has to be capable of being handled and of self support without slumping in the early stages of the test. In practice the upper limit of initial water content lies between the liquid and plastic limits, while the lower limit must be sufficiently above the shrinkage limit to clearly define the straight portion of the plot (line AB in Fig. 1).

The SHRINKiT measures the overall volume change of the test specimen by measuring its height and diameter at up to 3,600 points around its periphery. This is effectively a scan of the specimen where the calculation of volume is based on a 'stack of discs' model; the weight of the specimen being determined for each scan. A plot of water content versus volume may thus be produced, as for the BS1377:1990 (BSI, 1990) tests (Fig. 1), and the shrinkage limit determined using the same graphical construction (Head, 1992).

The SHRINKiT test method has the following advantages over mercury immersion methods BS1377:1990 (BSI, 1990):

- Hazardous materials and handling facilities are eliminated.
- The test specimen is handled only at the start and end of the test.
- Larger test specimens may be used (the TRL BS1377:1990 (BSI, 1990) method cannot test specimens much larger than 38 x 76 mm).
- Many more measurements can be obtained to define the shrinkage curve.
- Research capability can be added, for example decoupling the vertical and horizontal components of shrinkage, or the use of wetting/drying cycles in an environmental chamber.

The new test method has the following disadvantages:

- The current apparatus is expensive compared with BS1377:1990 (BSI, 1990) apparatus, but a cheaper version could be developed.
- Volume is derived rather than measured directly (by immersion).
- Only one specimen at a time may be tested using the current apparatus.

SHRINKAGE LIMIT TEST RESULTS

Thirty-six specimens, from several in-house BGS projects (Hobbs *et al.*, 2000; Jones *et al.*, 2006; Hobbs *et al.*, 2012), and from University of Leeds student theses (Kadir, 1997; Marchese, 1998), have been tested using version 1 or SHRINKiT. These have included British clay formations, glacial deposits, tropical clay soils and bentonite. Many of these samples were not capable of being tested using the TRL method and hence no comparative data are available. A full set of results for all shrinkage limits, and their associated index tests, are shown in Tables 1 & 2. Where available, the comparative tests show good correlation and there is every indication that the direct (immersion) method of volume measurement and the SHRINKiT method are comparable for all the soil types tested.

Table 1 Results of shrinkage limit (version 1) tests

Formation (state)	Location	w_o	w_L	I_P	$\mathbf{w_S}$ **v.1**	w_S BS1377	ΔV_{tot} v.1	ΔV_{tot} BS1377
		(%)	(%)	(%)	**(%)**	(%)	(%)	(%)
Gault (U)	Selborne	21.9	64.0	34.0	**15.5**	14.9	10.0	10.6
Gault (U)	Leighton Buzzard	41.6	88.4	44.8		24.0	15.4	
Gault (U)	Leighton Buzzard		94.0	54.0	**12.3**	11.4		
Mercia Mst. (U)	Gringley	16.7	37.0	14.0	**14.4**		4.4	
Mercia Mst. (U)	Gringley	17.7	36.7	14.3	**12.6**	12.6	6.7	
Mercia Mst. (C)	Gringley		40.0	19.0	**9.5**	9.5		
London Clay (U)	Newbury	25.8	59.0	30.0	**16.6**	17.7	9.1	12.8
Glacio-lacustr. (U)	Afon-Teifi	28.0	57.0	27.0	**20.6**	22.3	11.5	15.6
Lambeth (U)	Whitecliff	22	49.0	23.0	**12.3**	9.9	13.3	12.4
Lambeth (U)	Newbury	15.9	42.0	22.0	**8.1**		14.9	
Till (U)	Filey	13.9	30.2	14.3	**9.7**	8.8	7.4	
Bentonite (R)	Wyoming	146.4	332.0	294.0	**38.0**		58.0	
Latosol (U)	Java	57.9	114.0	46.0	**31.5**		22.4	
Latosol (C)	Java	66.0	114.0	46.0	**27.7**		34.4	
Andosol (U)	Java	87.1	83.0	27.0	**13.0**		7.8	
Andosol (C)	Java	89.5	83.0	27.0	**49.0**		29.7	

Key:
U Undisturbed
R Remoulded
C Compacted

Table 2 Results of shrinkage limit (SHRINKiT) tests

Formation (state)	Location	w_L	I_P	$\mathbf{w_S}$	R_S	w_0	S_n	ΔV_{tot}	I_S	LI	Ψ
		(%)	(%)	**(%)**	(g/mm³)	(%)	(%)	(%)	(%)		
Head (R)	East Leake (Notts.)	48.0	24.0	**9.3**	1.82	39.0	92.0	32.0	14.7	0.6	2.02
Till (U)	Reepham (Norfolk)	24.0	12.0	**9.9**	2.30	13.6	98.9	7.7	2.1	0.13	1.76
Till (U)	Spurn Point (Yorks.)	41.0	23.0	**10.5**	1.90	19.3	90.6	7.6	7.5	0.06	1.17
Till (U)	Aldbrough (Yorks.)	30.0	15.0	**9.4**	2.13	12.3	80.0	6.0	5.6	-0.18	0.52
Till (U)	Aldbrough (Yorks.)	37.0	20.0	**10.6**	2.09	16.6	93.4	10.7	6.4	-0.02	0.94
Till (U)	Aldbrough (Yorks.)	32.0	13.0	**16.2**	1.86	23.2	93.7	10.8	2.8	0.32	2.5
Till (R)	Aldbrough (Yorks.)	46.3	21.5	**15.0**	1.87	28.8	89.7	19.6	9.7	0.19	1.42
London (R)	Bulmer (Essex)	48.0	26.2	**19.1**	1.63	35.9	93.4	19.7	2.7	0.54	6.22
London (U)	Newbury (Wilts.)	65.0	39.0	**13.8**	1.61	26.1	75.4	12.5	12.2	0.00	1.01
London (R)	Colchester (Essex)	90.4	63.0	**16.8**	1.68	60.5	93.8	41.0	10.6	0.53	4.12
Reading (U)	Newbury (Wilts.)	54.0	32.0	**6.2**	1.85	21.1	92.0	8.5	17.8	-0.03	0.94
Gault (U)	Niton (I.O.W.) P71	67.0	39.0	**8.1**	1.68	25.1	88.5	8.0	19.9	-0.02	0.95
Gault (U)	Niton (I.O.W.) P71	68.0	41.0	**10.7**	1.58	28.9	84.3	10.8	16.3	0.05	1.12
Gault (U)	Niton (I.O.W.) P83	61.0	37.0	**10.9**	1.80	23.9	94.6	10.7	13.1	0.00	0.99
Gault (U)	Niton (I.O.W.) P83	69.0	47.0	**8.5**	1.80	23.3	90.7	11.0	13.5	0.03	1.10
Mercia (U)	Cropwell Bish.(Nott)	40.0	15.4	**11.1**	2.07	15.3	93.8	7.0	13.5	-0.6	0.31
Oxford (U)	Milton Keynes	53.0	25.9	**16.9**	1.77	30.5	101	16.3	10.2	0.13	1.33
Oxford (U)	Milton Keynes	61.0	31.0	**17.6**	1.71	35.3	98.0	20.3	12.4	0.17	1.43
Whitby (R)	Finedon (Northants)	61.0	35.0	**20.0**	1.78	51.4	90.5	39.1	6.0	0.73	5.23
Westbury (C)	East Leake (Notts.)	55.0	21.0	**11.3**	1.49	20.9	56.5	6.5	22.7	-0.62	0.42

Key:
U Undisturbed
R Remoulded
C Compacted

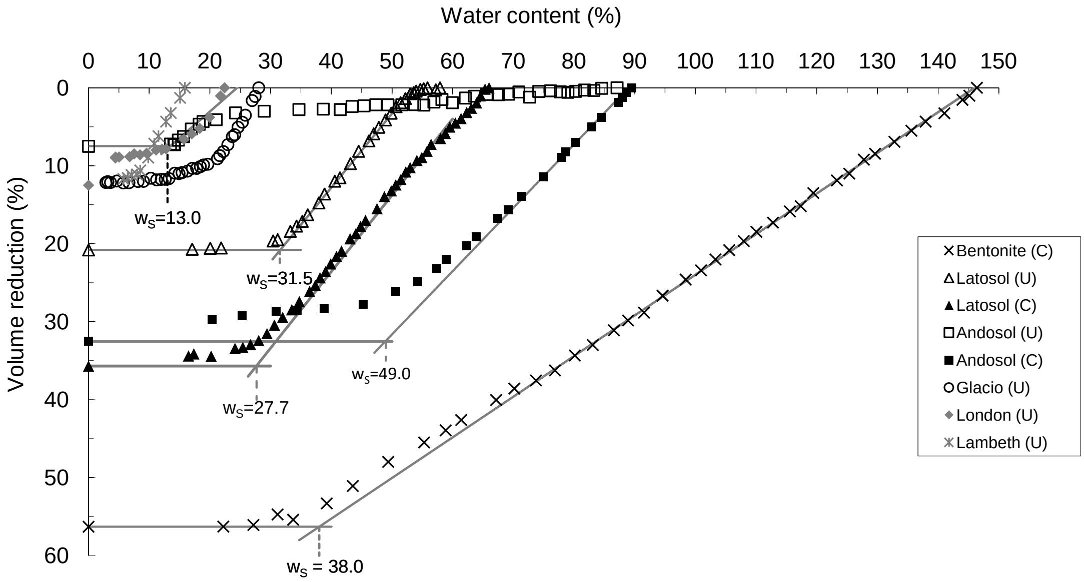

Figure 3 Plot of water content vs. volume reduction for version 1 tests on remoulded Wyoming bentonite and two tropical red clays from W. Java, Indonesia (undisturbed and compacted) showing shrinkage limit construction, plus three British clays for comparison. Refer to Table 1.

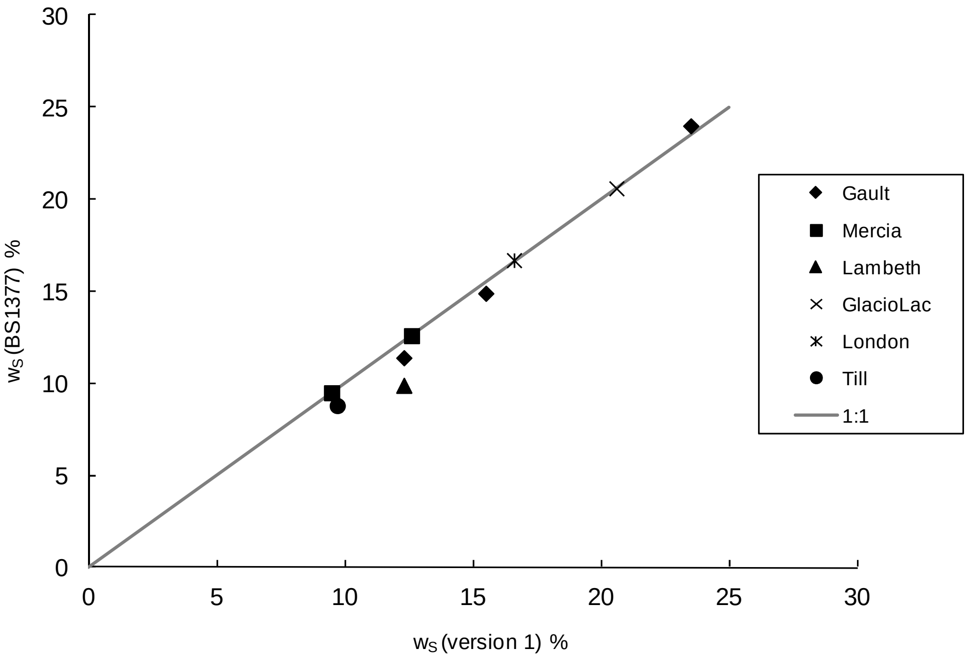

Figure 4 Comparison between version 1 and BS1377 shrinkage limit results

The data shown in Figs. 3 and 4 are taken from Table 1.

Results to date have given shrinkage limits ranging from 9 to 49%. Volumetric strains of between 4 and 58% have been measured. Samples with extremely high plasticity, for example Gault Formation and Wyoming bentonite, have tended to crack severely during the test. This has affected the shape of the shrinkage curve and may have affected the result. It has also highlighted the issue of whether the volume of fissures should be included in the 'volume' or whether the external surface alone should be taken irrespective. With extremely high plasticity samples the unusual situation occurs whereby volume reduction due to shrinkage is accompanied by volume increase due to development and opening of cracks, the net change being reasonably well measured by the test in most cases. In practice, such samples (Fig. 5) would be deemed untestable within the principles of the BS (or other) immersion tests.

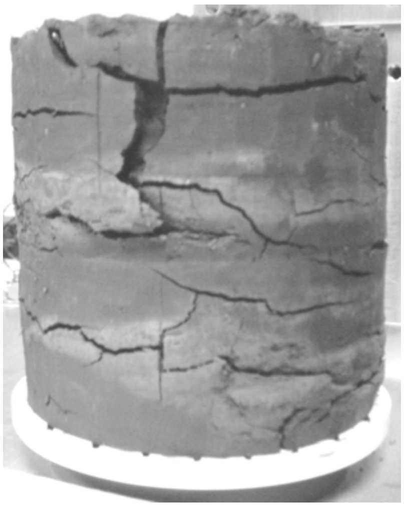

Figure 5 Example of heavily fractured SHRINKiT (undisturbed) test specimen, post-test

The Casagrande plasticity chart for selected shrinkage samples is shown in Fig. 6. The results of the SHRINKiT tests are shown in Fig. 7. These reveal the characteristic 'hockey stick' shape of the mid and lower parts of the soil-water characteristic curve (Fredlund & Xing, 1994). The tendency is for the early (high water content) parts of the curves to be coincident whilst the later (low water content) parts diverge at or near the air entry point.

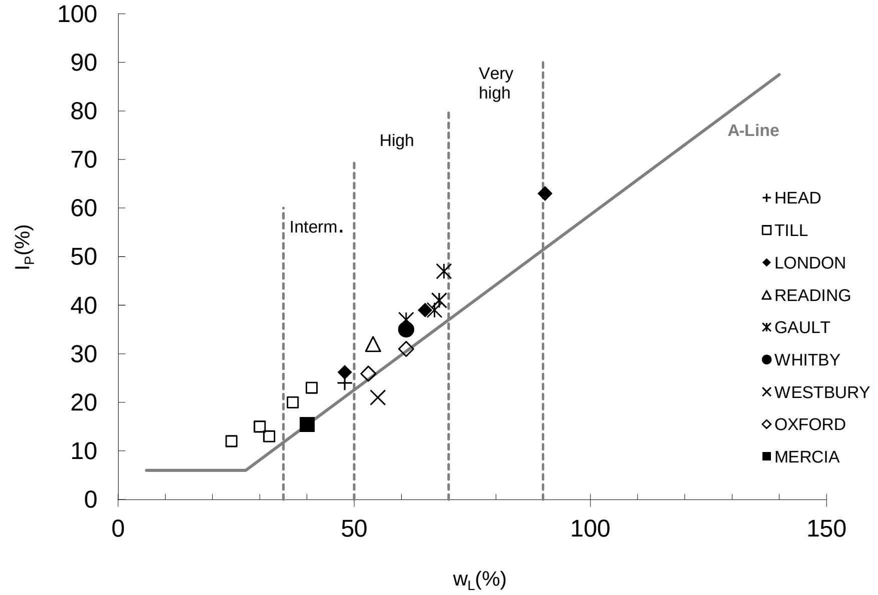

Figure 6 Casagrande plasticity plot for SHRINKiT test samples

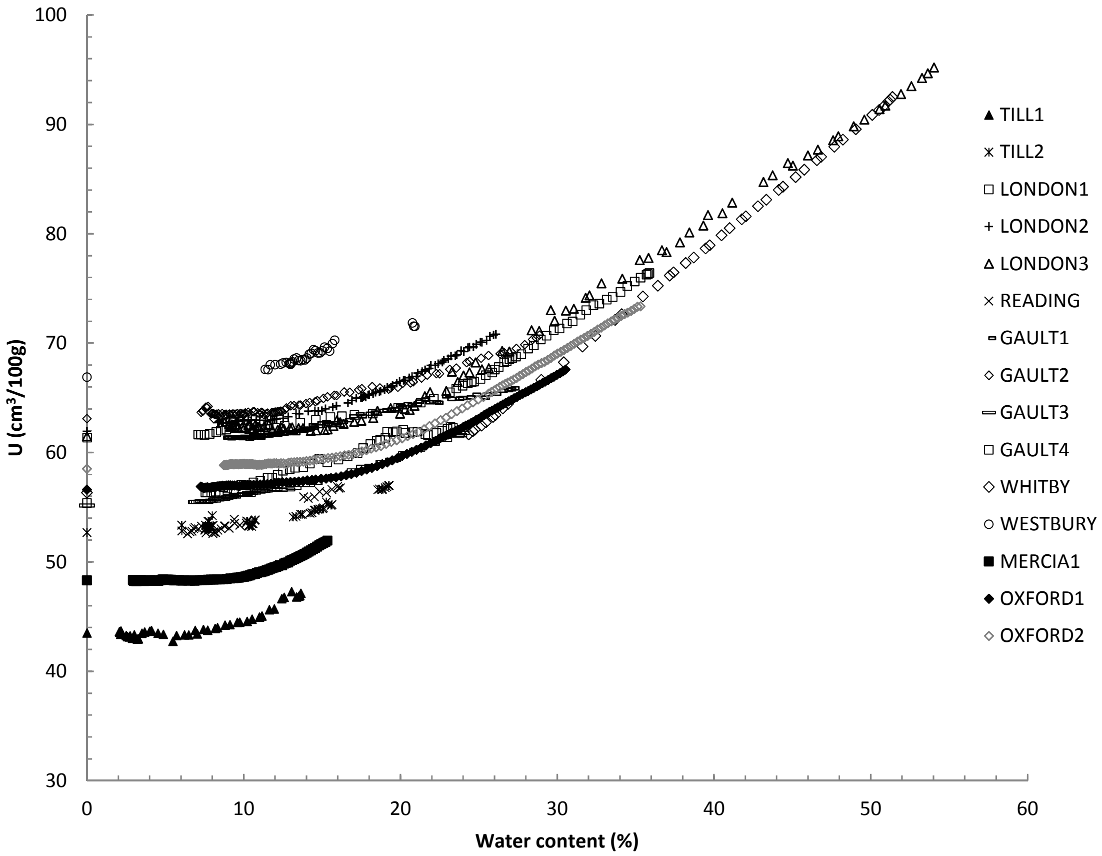

Figure 7 Plot of Water content vs. Volume per 100g dry soil, U for selected British soils (SHRINKiT shrinkage limit test)

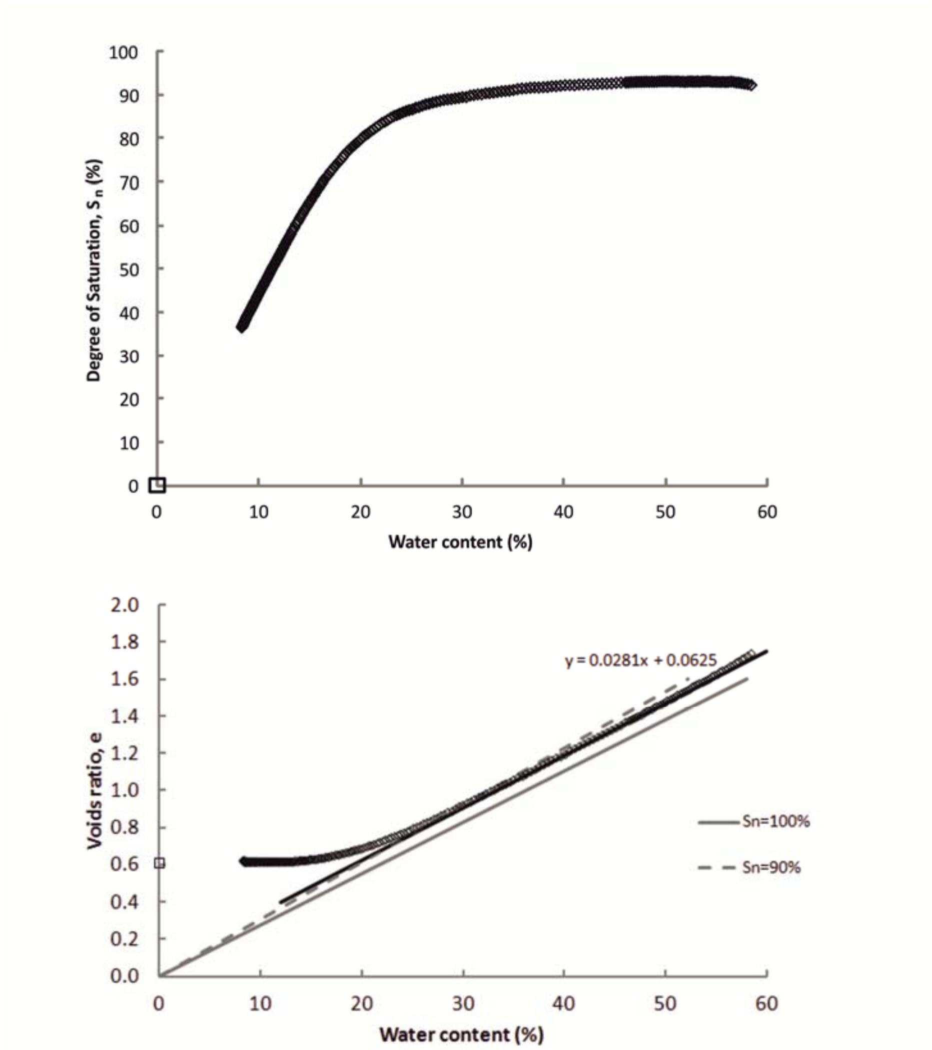

Figure 8 Changes in saturation and voids ratio during SHRINKiT shrinkage limit test (Remoulded London Clay Formation, Colchester; w_L = 90.4%, w_P = 27.4%, w_S = 19.9%)

An example of the changes in saturation taking place during the shrinkage test is shown in Fig. 8. The straight black line is the best-fit to the straight portion of the experimental plot. The grey lines are for the condition of 100% and 90% degree of saturation (for Gs = 2.76). The air entry point according to Braudeau *et al*., (1999) is the minimum water content at which the soil remains saturated under atmospheric conditions. This should therefore be where the experimental shrinkage curve starts to depart from the straight line and the degree of saturation starts to reduce rapidly (Ho & Fredlund, 1989; Fredlund & Rahardjo, 1993). This would lie somewhere between 35 and 40% water content, placing it well above the plastic limit which does not match the interpretation of Sridharan & Prakash (1998a) whereby the air entry point lies just above the shrinkage limit. The most likely interpretation is that the air entry point is the point below which *significant* loss of saturation takes place. This would place it closer to the shrinkage limit as indicated by Sridharan & Prakash (1998a) and probably on the point of maximum slope change in the saturation plot; in a similar manner to the analysis of an e-logP plot in the consolidation test.

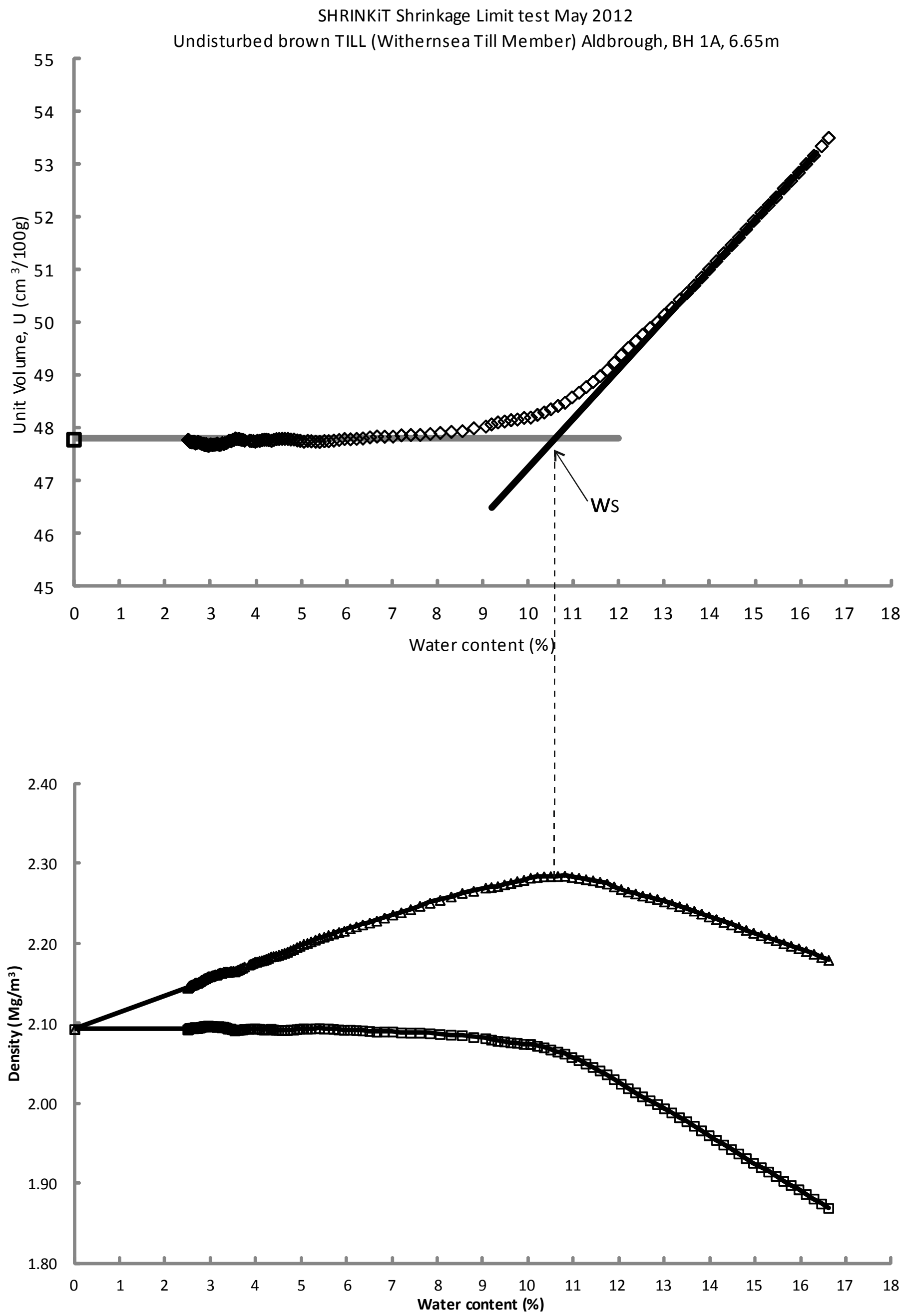

Figure 9 Comparative plots of unit volume and bulk & dry density vs. water content for a SHRINKiT test on till (undisturbed).

It is noted that the shrinkage limit (Fig. 9, upper) matches the maximum bulk density of the specimen (Fig. 9, lower). This point also matches the point of maximum curvature on the dry density curve.

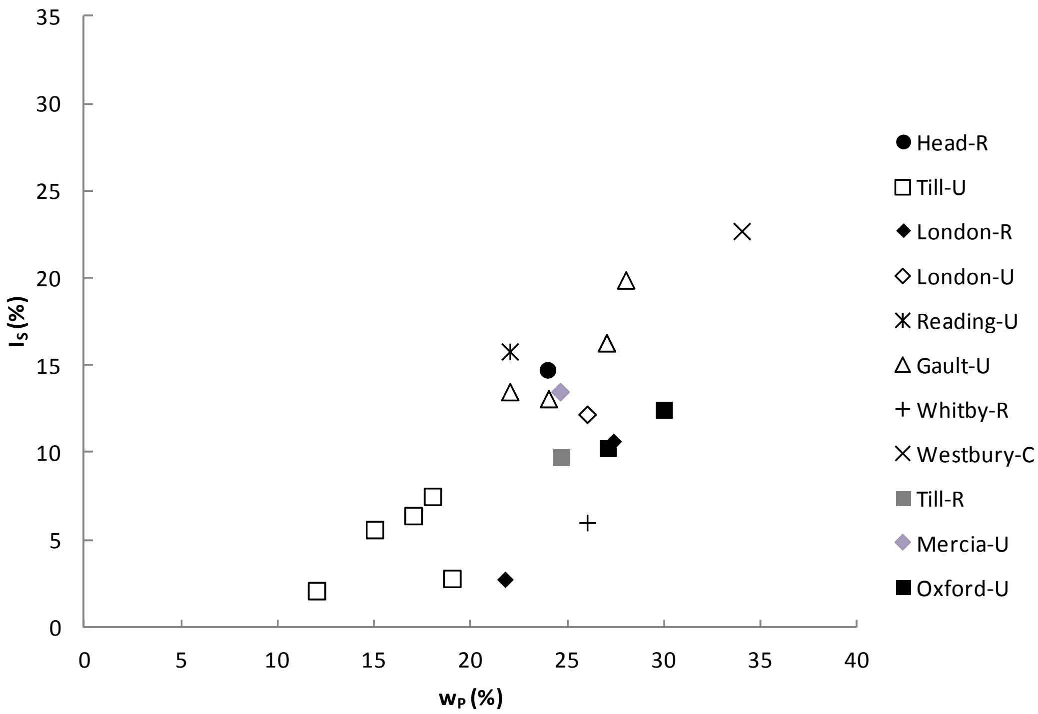

Figure 10 Plot of plastic limit vs. shrinkage index (by formation) for SHRINKiT tests

A plot of plastic limit vs. shrinkage index is shown in Fig. 10. This plot is equivalent to the Casagrande plot of liquid limit vs. plasticity index. The equation of the 'best-fit' line for the undisturbed samples is as follows:

$$I_S = 0.78(w_P - 8.3) \quad (1)$$

n = 14, R^2 = 0.63, SE = 0.17, p = 0.0007

This is close to the equation for the 'upper-bound' B-line often quoted for the Casagrande plot (Head, 1992; Reeves et al., 2006):

$$I_P = 0.9(w_L - 8) \quad (2)$$

The equation of the 'best-fit' line for the remoulded samples (Fig. 10) is as follows:

$$I_S = 0.86(w_P - 17.2) \quad (3)$$

n = 5, R^2 = 0.51, SE = 0.35, p = 0.048

This could be considered equivalent to the Casagrande A-line which has the equation:

$$I_P = 0.73(w_L - 20) \quad (4)$$

However, the relationship is poor, reflecting the paucity of measurements.

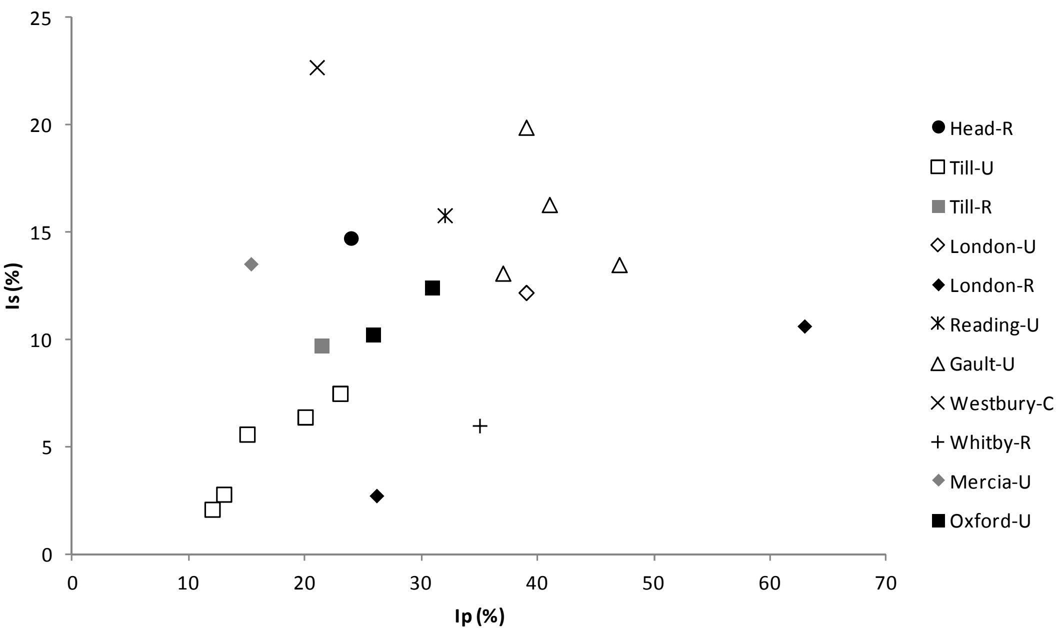

Figure 11 Plot of plasticity index vs. shrinkage index for SHRINKiT tests. U=undisturbed, R=remoulded, C=compacted

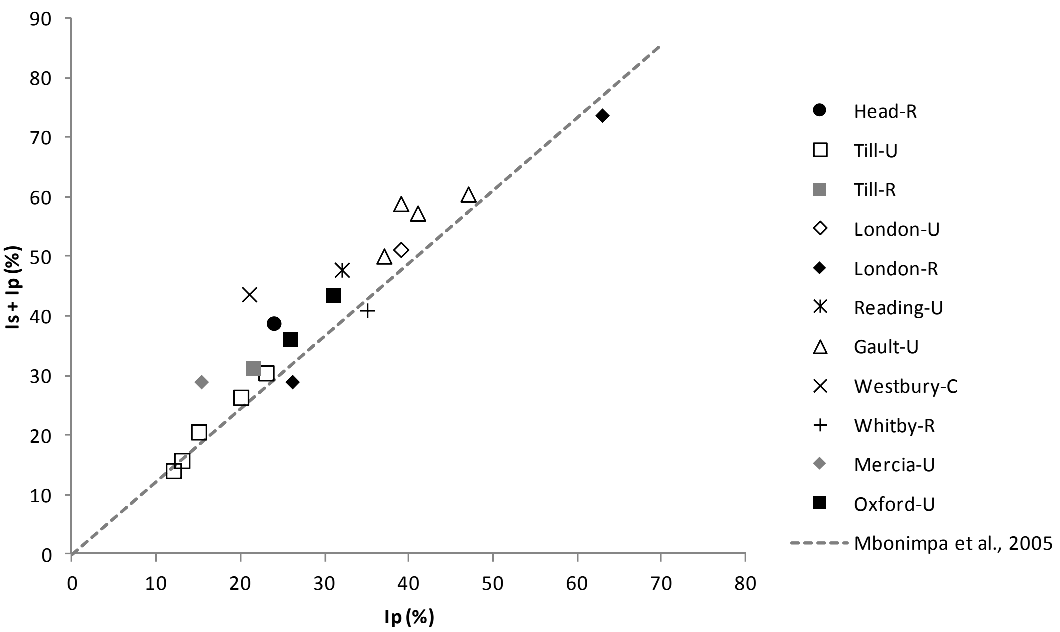

Figure 12 Plot of plasticity index vs. shrinkage index + plasticity index for SHRINKiT tests. U=undisturbed, R=remoulded, C=compacted

A plot of plasticity index vs. shrinkage index is shown in Fig.11. This shows a rather poor correlation, with remoulded London Clays being notable amongst the outliers. A plot of plasticity index vs. shrinkage index + plasticity index is shown in Fig. 12. This shows a much better positive correlation which is similar to that reported by Mbonimpa *et al*. (2005) for indirect determination of shrinkage limit from the Casagrande chart for a variety of remoulded Canadian soils (Note: definition of shrinkage index in Mbonimpa *et al*., 2005 differs from that used here).

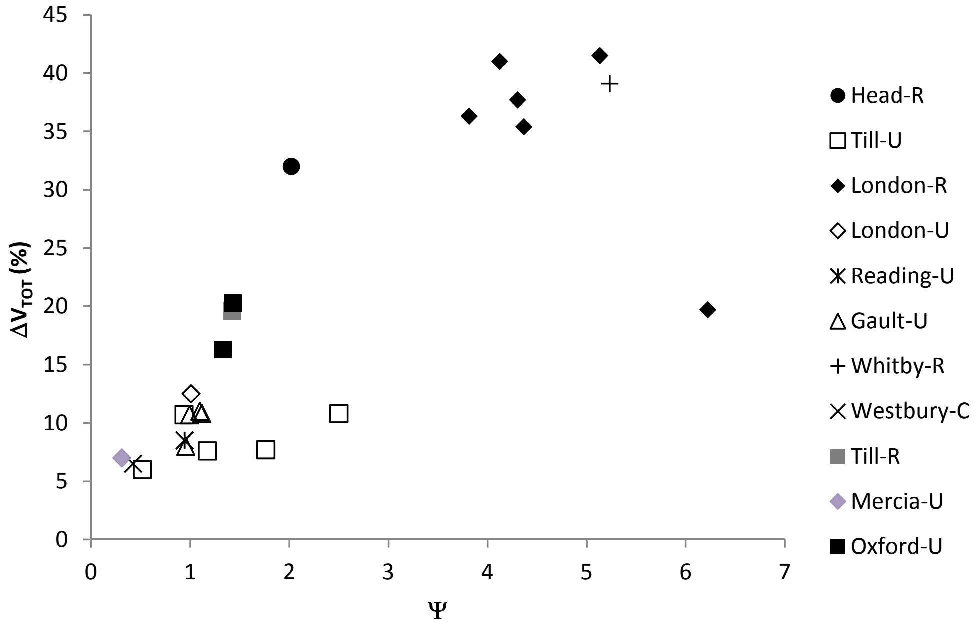

Figure 13 Plot of shrinkability index vs. volumetric strain (by formation) for SHRINKiT tests. U=undisturbed, R=remoulded, C=compacted

If shrinkability index, is defined as follows,

$$\Psi = \frac{(w_0 - w_S)}{I_S} \tag{5}$$

then a plot of shrinkability index vs. volumetric strain for the SHRINKiT tests is shown in Fig. 13. This shows a reasonable positive correlation, albeit with insufficient data to characterise each formation statistically. Taken together the data gave the following:

$$\Delta V_{TOT} = 12.76\ln(\Psi) + 12.9 \tag{6}$$

$n = 24, SE = 1.87, p = 7.6 \times 10^{-7}$

CONCLUSIONS

The SHRINKiT test has been shown to measure the shrinkage limit of a clay soil in a geotechnical framework within acceptable levels of accuracy using a safe method. This method provides an alternative to the current BS methods and equivalent mercury immersion methods used worldwide. A wide range of shrinkage behaviour has been demonstrated comparing British and tropical clays. It is likely that some types of extremely high plasticity clays are untestable following the principles of the BS tests. Some basic relationships have been explored with other common Atterberg parameters and with the shrinkage equivalents of plasticity and liquidity indices. The unequivocal establishment of line AB (Fig. 1) is crucial to obtaining the correct test result. The large number of measurements possible with SHRINKiT allows this, and may also allow interpretation of the air-entry point, particularly in the light of Haigh *et al.* (2013). The basis for renewed research in the field of geotechnics has been established, particularly with regard to the significance of the shrinkage limit and also shrinkage anisotropy and the relative behaviour of undisturbed and remoulded samples. Determination of colour change and crack development will also be incorporated.

NOTATION

G_S	Specific gravity
I_P	Plasticity index
I_S	Shrinkage index (= w_P - w_S)
L_S	Linear shrinkage
n	Number of samples
p	p-value
R_S	Shrinkage ratio
S_n	Degree of saturation
w_0	Water content at start of test
w_L	Liquid limit
w_P	Plastic limit
w_S	Shrinkage limit
Ψ	Shrinkability index
ΔV_{tot}	Volumetric strain (total volume reduction during test, *dependent on w_0*)
BGS	British Geological Survey
BS	BS1377 preferred method (TRL apparatus)

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