Shrinkage limit test results and interpretation for clay soils

Shrinkage limit of clay soils

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Abstract:

The shrinkage limit is one of the Atterberg limits and is a fundamental geotechnical parameter used for the assessment of the settlement of clay soils due to reduction in water content, yet is rarely tested for as part of ground investigation. This paper describes shrinkage limit test results on a variety of soils from Britain and overseas obtained using an improved laboratory testing procedure developed at the British Geological Survey (BGS). The co-relationships with the other Atterberg limits and with density are explored. In particular, the coincidence of the shrinkage limit with the water content at the peak bulk density achieved in the test is examined. The shrinkage behaviour for undisturbed and remoulded states and a 3-way relationship between water content, density and suction are demonstrated. Some tropical residual and highly smectitic soils show a very wide range of shrinkage behaviour, albeit for a small dataset, when compared with the larger dataset of temperate soils tested. Consideration is given to limitations of the new and existing test methods.

Many towns, cities, transport routes and buildings are founded on clay-rich soils and rocks. The clays within these materials may be a significant hazard to engineering construction due to their ability to shrink or swell with changes in water content (Anon 1993; Jones & Jefferson, 2012). This paper follows an earlier paper (Hobbs *et al.* 2014) which described the development of an improved test method for determining the shrinkage limit of clay soils, entitled 'SHRINKiT', and introduced a small dataset of test results. It covers new test results on a wider range of soils using the same test methods and expands the interpretation and analysis of results to include comparative undisturbed /remoulded results and relationships with the other Atterberg limits and suction test results. The thrust of this research is to encourage the measurement of this important index parameter using a safe and accurate method, and for its application to be more widespread in building and engineering.

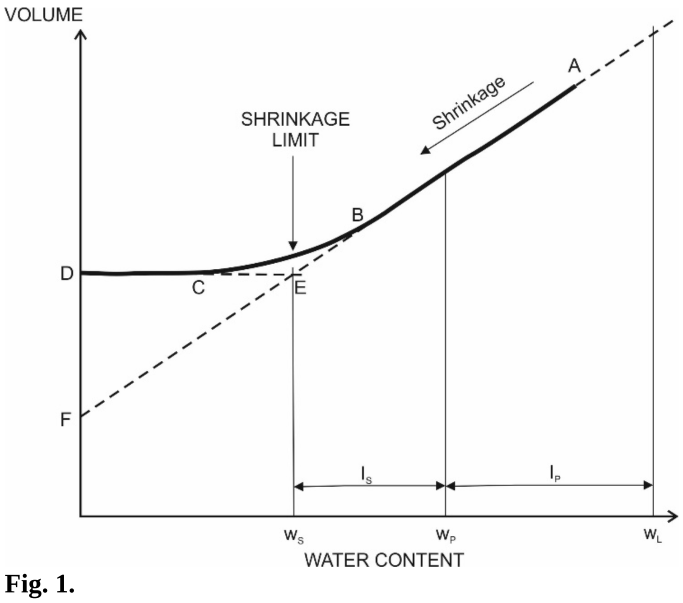

Fig. 1.

The shrinkage limit was one of seven state limits originally conceived by Albert Atterberg (Atterberg, 1911a, 1911b) and further described by Casagrande (1948) and one of three that are currently covered by test standards (e.g. BSI 1990, ASTM 2018). The shrinkage limit of fine soil (w_s) is conceptually defined as the water content at which the phase of the soil changes from the 'semi-solid' to the 'solid' state (Sridharan & Prakash 1998). This is graphically illustrated in Fig. 1 where continuous reduction in water content results in no further volume change. The shrinkage from A to B is where volume reduction matches water loss. The gradient of the line AB is the initial degree of saturation, S_n if volume change is expressed as voids ratio and, if volume change is expressed as a percentage of dry volume, equals the shrinkage ratio, R_S. Point D is the oven dried state (105°C) and point E defines the shrinkage limit (BSI 1990) at the graphical intercept of lines AB and CD. Point B, usually referred to as the air-entry point (Haigh *et al*. 2013), represents the water content at which water loss outstrips volume reduction and the degree of saturation starts to reduce significantly. The shrinkage limit also coincides with the point of peak bulk density achieved during the test (discussed later).

The two British Standard methods for measuring shrinkage limit directly employ Archimedes principle applied to a mercury bath in order to determine the volume of the specimen, BS 1377-2, tests 6.3 and 6.4 (BSI 1990). Both methods use mercury and, therefore, have health and safety risks associated with them, including the disposal of the contaminated sample. Whilst the Standard does not specify that the tests should be just be on remoulded samples (as for the other Atterberg limits - liquid and plastic limits), the intention is implicit. However, there is no technical reason why undisturbed samples cannot be used and, undisturbed samples, in addition to remoulded samples, have been used in this study. Also, the results on undisturbed samples might have more application for engineering purposes. The Standard method uses a mercury cell originally developed by the Transport Research Laboratory, TRL (Road Research Laboratory 1952; Ackroyd 1969). 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) and utilised worldwide (e.g. Mishra & Sridharan 2017), also uses mercury immersion and the same graphical construction. Other methods based on 'coated-clod' specimens have been used: employing immersion (ASTM 2008; Sridharan & Prakash 2009), laser scanning (Rossi *et al.* 2008) and optical scanning (Sander & Gerke 2007; Stewart *et al.* 2012). The current ASTM method (D4943-08) employs a hot wax coating Archimedes immersion technique where shrinkage limit is calculated solely from the initial and oven-dried states (ASTM 2008). This type of immersion method is destructive, unlike the scanning methods, and assumes that the initial specimen is remoulded and fully saturated and that the line AB in Fig. 1 is straight. Whilst the shrinkage limit is mentioned in current Eurocode 7 documents, the methods of testing are not described.

A new automated laboratory test apparatus for the determination of shrinkage limit, entitled SHRINKiT, was developed to provide a safer and more accurate method than those previously available and to promote the use of an important but under-utilised test. This, along with a preliminary data set, was described in Hobbs *et al.* (2010). The fundamental aspects of shrinkage behaviour were further examined by Hobbs *et al*. (2014) using the 'SHRINKiT' method of testing which was validated using a limited preliminary data set. The method employs a simple form of laser scanner and a digital balance to measure volume and weight, respectively. A large number of volume and weight measurements are made over a period of several days while the specimen air-dries. Cylindrical specimens (nominally 100 x 100 mm) taken from remoulded or undisturbed samples are used; the latter prepared from class 1, undisturbed samples (BSI, 2015) prepared by hand trimming in trial pits or from rotary drilled core and preserved to ensure no or minimal water loss,.

Method

The shrinkage limit tests were carried out in the laboratory using the BGS's computer automated SHRINKiT method (Hobbs *et al*. 2014; Hobbs *et al*. 2010). This measures specimen mass and volume simultaneously, the former with an integral digital balance to 0.01g and the latter using a travelling laser rangefinder and rotating specimen platform which combine to act as a scanner. This enables a large number of readings per test that is used to definite the volume-water content plot to air dried and of the oven dried sample, and the graphical construction to determine shrinkage limit (Fig. 1). A single cylindrical specimen (100 x 100 mm) taken from a remoulded or undisturbed sample is used (10% larger or smaller specimens can be accommodated). The apparatus is calibrated using plain and contoured aluminium cylinders of known weight and volume. Average errors of 0.015 % and 0.07 % were obtained for weight and volume, respectively, using five different calibration cylinders, and the software version (v2.5.2) and the laser point density (300 per scan) used during the tests described here. The calculation used in the ASTM test D4943-08 'wax' method (ASTM 2008) when applied to the SHRINKiT data allowed a comparison to be made with the SHRINKiT results. The other soils index tests were carried out according to BS1377 (BSI: 1990, Part 5). The 'suction' tests were carried out using a Soil Moisture Equipment Corporation 1500F1 (1500 kPa capacity) ceramic plate extractor on a selection of remoulded shrinkage limit sub-samples at water contents close to their liquid limit. Seven stages were carried out from 100 to 1500 kPa and a best-fit curve applied. All tests were conducted in the laboratory at a constant 20^{o}C.

As described earlier, the ASTM method (ASTM 2008) employs an Archimedes immersion technique applied to a disc-shaped specimen of remoulded soil, first air-dried, then oven-dried and coated in hot wax. The calculation employed assumes that the initial degree of saturation is 100% and that the initial condition (Point A in Fig. 1) falls on a straight line through Point E (Fig. 1). In addition to the normal graphical construction (Fig. 1), the final calculation from D4943-08 has been applied to the SHRINKiT data using the following formula:

$$w_s = w_0 - \left[\frac{(V_0 - V_d)\rho_w}{m_s}\right] x100 \qquad (1)$$

where w_S, Shrinkage limit; w_0, Initial water content; V_0, Initial volume; V_d, Oven dry volume; ρ_w, Density of water; m_s, Oven dry mass.

Samples

Undisturbed

As SHRINKiT makes strain measurements test on non-remoulded samples were carried out on 'class 1' undisturbed samples (BSI 2015; Baldwin & Gosling 2009); that is, samples of a quality required for effective shear strength and stiffness testing, or remoulded samples prepared according to BS methods (BSI 2007). In general, undisturbed samples that are not class 1 or 2, or have not been stored correctly, are not suitable for undisturbed testing using the SHRINKiT method. All undisturbed test samples used in this research were class 1 or 2 and preserved from water loss prior to testing and stored in controlled temperature and humidity conditions. The majority of samples were hand-trimmed from blocks prepared in trial pits and collected by BGS, unless stated otherwise.

Remoulded

Remoulded samples were prepared by hand from matching undisturbed samples according to BS methods (BSI 2007). The principal difference between undisturbed and remoulded samples in the SHRINKiT test is that the former retain their structural features, whereas the latter have been remoulded as if for preparation for liquid and plastic limit.. In addition, the water content of remoulded samples can be controlled during preparation. These factors are usually reflected in the form of the shrinkage curve, the shrinkage limit result itself and the volumetric strain; though this is dependent on the starting water content. In the case of structured, metastable and aggregated soils, such as the tropical red clay samples the differences can be significant.

Results

Following the preliminary set of test results described in Hobbs *et al*. (2014), a further thirty-two tests were carried out using the SHRINKiT apparatus, details and results for which are tabulated in Table 1 and Table 2, and plots for selected tests illustrated in Figs. 2 and 3. Shrinkage limits ranged from 14.3 to 41.1 % for remoulded samples and 7.7 to 30.9 % for undisturbed samples. Volumetric strains (dependent on initial water content, w_0) ranged from 2 to 23 % for undisturbed samples and from 18 to 52 % for remoulded samples. Formations and soil types are seen to occupy discrete zones within Fig. 4, notably the large zone for undisturbed tropical red clay which, though not populated, may indicate the possible range for such soils as allophanic andosols which, in their undisturbed state, have aggregated and metastable fabrics. Abbreviations for test parameters are explained under 'Notation'. Interruptions in plots are due to technical issues during tests.

Table 1. *Description of samples used for SHRINKiT tests*

Sample No.	Location	Formation	+NGR
Till_slip	Aldbrough, East Riding of Yorkshire, GB	Holderness (landslipped)	525667, 439523
Till6	Aldbrough, E Riding of Yorkshire, GB (BH3b, 2.5m)	Holderness (Withernsea Member)	525667, 439523
Till7	Aldbrough, E Riding of Yorkshire, GB (BH3b, 6.8m)	Holderness (Withernsea Member)	525667, 439523
Till8	Aldbrough, Riding of Yorkshire, GB (BH3b, 11.5m)	Holderness (Skipsea Till Member)	525667, 439523
Till9	Aldbrough, E Riding of Yorkshire, GB (BH3b, 14.6m)	Holderness (Skipsea Till Member)	525667, 439523
Till10	Aldbrough, E Riding of Yorkshire, GB (BH3b, 16.6m)	Holderness (Bridlington Member)	525667, 439523
London8	Knoll Manor Pit, Dorset, GB	London Clay	397700, 797300
London9	Poyle Quarry, Berkshire, GB	London Clay	502800, 176600
London10	Stanwell Quarry, Surrey, GB	London Clay (Palaeostrat. Div.: B1)	504900, 174600
London11	Hollingson Meads Quarry, Essex, GB	London Clay (Palaeostrat. Div.: A)	545300, 226000
London12	Hollingson Meads Quarry, Essex, GB	London Clay (Palaeostrat. Div.: A)	545300, 226000
London13	Ockendon Quarry, Surrey, GB	London Clay (Palaeostrat. Div.: A)	561400, 182000
London14	Fair Oak Pit, Southampton, Hampshire, GB	London Clay	450400, 118300
London15	Fair Oak Pit, Southampton, Hampshire, GB	London Clay	450400, 118300
London16	Knowl Hill Quarry, Berkshire, GB	London Clay	481600, 179500
Oxford3	Christian Malford, Wiltshire, GB (BH3, 5.1 m)	Oxford Clay (Peterborough Member)	397676, 179259
Oxford4	Christian Malford, Wiltshire, GB (BH3, 5.1 m)	Oxford Clay (Peterborough Member)	397676, 179259
Oxford5	Christian Malford, Wiltshire, GB (BH2, 2.5 m)	Oxford Clay (Peterborough Member)	398251, 179606
Oxford6	Christian Malford, Wiltshire, GB (BH2, 2.5 m)	Oxford Clay (Peterborough Member)	398251, 179606
TropRed1	Subang, Java, Indonesia (Pit 12, 3.0 m)	*Ferralsol* (Older Quaternary Volcanics)	786950, 274200
TropRed2	Subang, Java, Indonesia (Pit 12, 3.0 m)	*Ferralsol* (Older Quaternary Volcanics)	786950, 274200
TropRed3	Lembang, Java, Indonesia (Pit 11, 5.0 m)	*Andosol* (Younger Quaternary Volcanics)	786950, 246400
TropRed4	Lembang, Java, Indonesia (Pit 11, 5.0 m)	*Andosol* (Younger Quaternary Volcanics)	786950, 246400
TropRed5	Subang, Java, Indonesia (Pit 12, 5.0 m)	*Ferralsol* (Older Quaternary Volcanics)	786950, 274200
TropRed6	Subang, Java, Indonesia (Pit 12, 5.0 m)	*Ferralsol* (Older Quaternary Volcanics)	786950, 274200
Kannav1	Melamiou, Paphos District, Cyprus (BH4, 5.0 m)	Kannaviou	460203, 386267
Kannav2	Melamiou, Paphos District, Cyprus (BH4, 5.0 m)	Kannaviou	460203, 386267
Melange1	Arodhes, Paphos District, Cyprus (BH16, 5.0 m)	Kathikas (landslipped)	443028, 386467
Brickearth	Ospringe Pit, Faversham, Kent, GB (0.5 m)	Upper Brickearth, non-calc (reworked loess)	599700, 161164
QuickClay	Norway*		
Ostend1	Happisburgh, Norfolk, GB	Happisburgh (Ostend Clay Member)	638549, 330815
Gault5	Arlesey, Bedfordshire, GB (BH1, AR1, 15.9 m)	Gault	518870, 234630

* Sample provided by Norwegian Geotechnical Institute (NGI);
NGR, National Grid Reference for the country of sample origin,
.

Table 2. *Results of shrinkage limit (SHRINKiT) test and other index tests*

Sample	State	**w_S (%)**	w_L (%)	I_P (%)	R_S (Mg/m^3)	w_0 (%)	S_{n0} (%)	ΔV_{tot} (%)	I_S (%)	LI	Ψ
Till_slip	Rem	**15.0**	46	22	1.87	28.8	89.7	20	9.7	0.19	1.4
Till6	Und	**12.0**	37	17	2.02	15.4	85.9	6	8.0	-0.27	0.4
Till7	Und	**11.4**	36	19	2.06	16.9	97.5	11	5.6	-0.01	1.0
Till8	Und	**11.2**	32	16	2.07	14.6	99.0	7	4.8	-0.09	0.7
Till9	Und	**13.1**	31	15	1.99	17.5	98.5	9	2.9	0.10	1.5
Till10	Und	**13.5**	31	15	1.98	16.4	99.8	6	2.5	0.03	1.2
London8	Rem	**15.5**	41	22	1.80	35.6	93.6	26	3.0	0.77	6.7
London9	Rem	**16.0**	79	55	1.73	51.8	92.3	38	8.0	0.51	4.5
London10	Rem	**16.9**	75	48	1.80	60.1	94.7	44	10.2	0.69	4.8
London11	Rem	**15.8**	55	29	1.82	57.1	96.2	43	9.9	1.07	4.2
London12	Und	**9.4**	55	29	1.65	21.6	82.1	5	16.3	-0.14	0.8
London13	Rem	**17.6**	76	49	1.75	56.9	91.2	40	9.4	0.61	4.2
London14	Und	**7.7**	47	27	1.70	22.2	93.9	3	12.7	0.07	1.1
London15	Rem	**18.2**	47	27	1.73	29.8	88.8	18	2.2	0.35	5.3
London16	Und	**16.8**	74	46	1.77	25.6	88.3	14	11.2	-0.5	0.8
Oxford3 *	Und	**15.7**	61	36	1.83	20.9	90.3	9	9.3	-0.11	0.6
Oxford4 *	Rem	**14.4**	61	36	1.82	43.1	93.3	34	10.6	0.5	2.7
Oxford5 †	Und	**14.7**	43	24	1.93	22.1	95.4	13	4.3	0.13	1.7
Oxford6 †	Rem	**14.3**	43	24	1.86	35.1	91.4	28	4.7	0.67	4.4
TropRed1 *	Und	**27.4**	109	53	1.33	45.1	85.6	15	28.6	-0.21	0.6
TropRed2 *	Rem	**26.7**	109	53	1.46	68.2	87.3	37	29.3	0.23	1.4
TropRed3 †	Und	**26.4**	126	28	0.74	101	79.5	17	71.6	0.13	1.1
TropRed4 †	Rem	**41.1**	126	28	1.16	79.8	92.8	29	56.9	-0.65	0.7
TropRed5 *	Und	**30.9**	101	45	1.21	44.0	78.1	12	25.1	-0.27	0.5
TropRed6 *	Rem	**35.4**	101	45	1.32	86.4	101	39	20.6	0.68	2.5
Kannav1 †	Und	**10.3**	121	65	1.56	37.0	83.8	23	45.7	-0.29	0.6
Kannav2 †	Rem	**18.7**	121	65	1.63	86.0	95.5	52	37.3	0.46	1.8
Melange1	Und	**11.0**	47	25	2.04	16.3	86.8	8	11.0	-0.23	0.5
Brickearth	Und	**9.9**	39	16	1.61	18.5	69.5	3	11.1	-0.28	0.8
QuickClay	Und	**13.9**	31	12	1.88	25.5	40.4	7	5.1	0.54	2.3
Ostend1	Und	**14.3**	28	9	1.59	23.3	91.1	2	4.7	0.48	1.9
Gault5	Rem	**25.2**	75	48	1.56	61.3	95.8	36	2.0	0.70	20.0

* † indicate matched undisturbed/remoulded samples; Und, Undisturbed; Rem, Remoulded.
Refer to 'Notation' section for geotechnical parameter abbreviations.

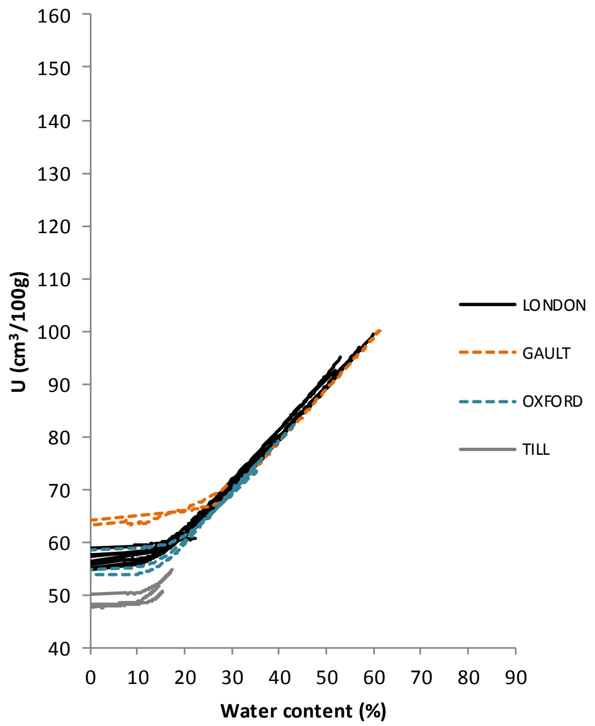

Fig. 2.

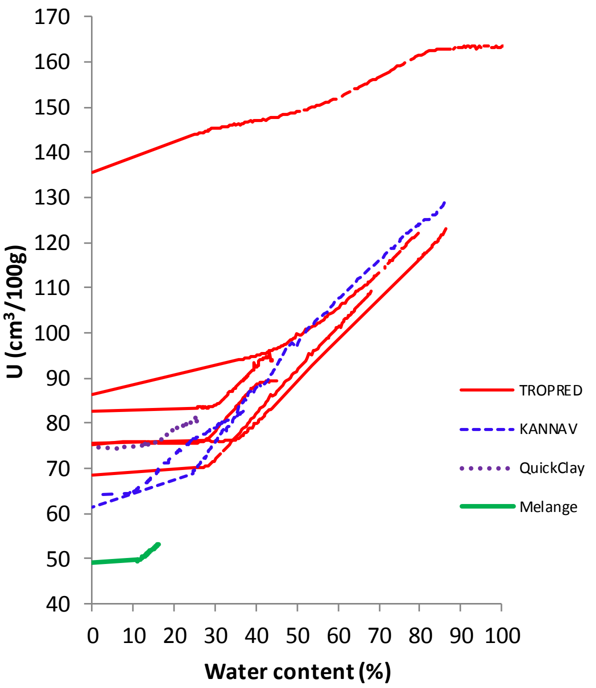

Fig. 3.

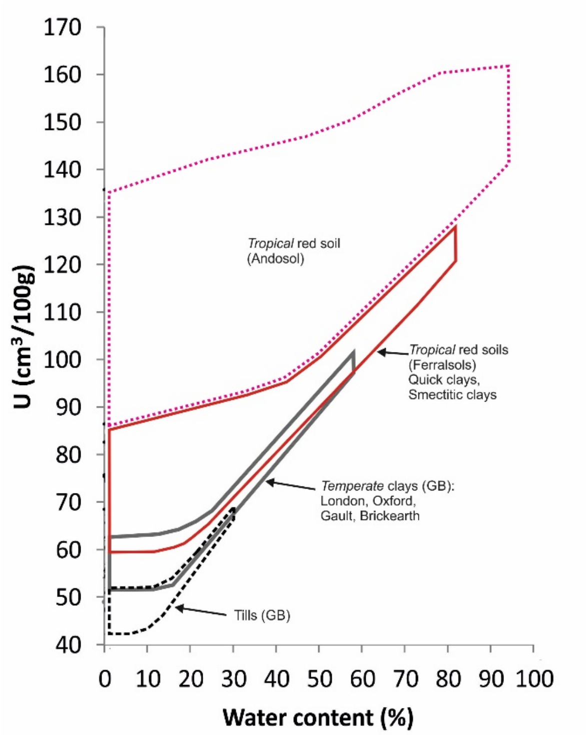

Fig. 4.

Shrinkage sensitivity

A limited number of 'matched pair' samples were tested to examine shrinkage limit 'sensitivity'; that is, the change in value from the undisturbed to the remoulded state. The results from these paired samples are shown in Table 3. Sensitivities are positive (i.e. remoulded value greater than undisturbed) with the exceptions of the Oxford Clay

Formation samples and TropRed 1 & 2 samples where sensitivities were slightly negative (i.e. remoulded value less than undisturbed), though probably within margins of error for the test method.

Table 3. *Shrinkage limit sensitivities for 'matched' undisturbed and remoulded samples*

Samples	w_s (Und) %	w_s (Rem) %	Sensitivity %
LONDON 12 & 11	9.4	15.8	+68
LONDON 14 & 15	7.7	18.2	+136
OXFORD 3 & 4	15.7	14.4	-8
OXFORD 5 & 6	14.7	14.3	-3
KANNAV 1 & 2	10.3	18.7	+82
TROPRED 1 & 2	27.4	26.7	-3
TROPRED 3 & 4	26.4	41.1	+56
TROPRED 5 & 6	30.9	35.4	+15

Und, Undisturbed; Rem, Remoulded

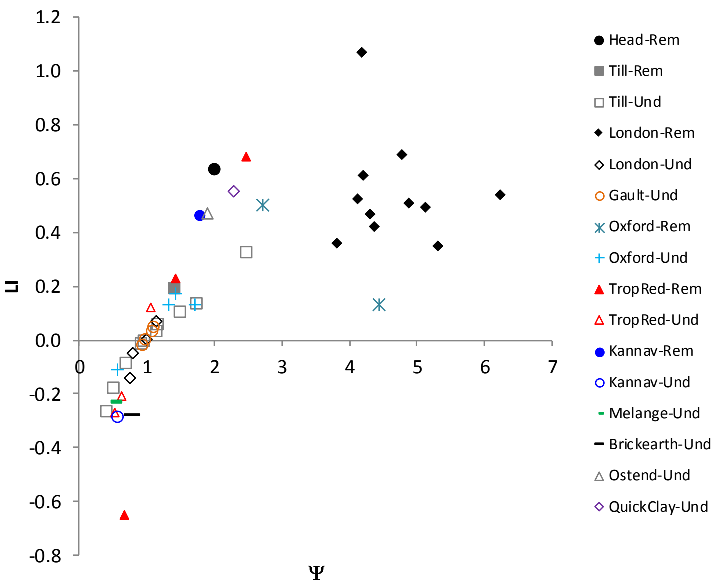

Fig. 5.

The shrinkability index, Ψ is defined in equation 2:

$$\Psi = \frac{(w_0 - w_s)}{I_s} \quad (2)$$

where w_0, initial water content;
w_s, shrinkage limit;
I_s, shrinkage index (equation (3).

$$I_s = w_P - w_S \quad (3)$$

Shrinkability index is a measure of the initial water content of the tested specimen in relation to the shrinkage index and is here defined in the same way that liquidity index relates water content to plasticity index. The relationship between shrinkability index and liquidity index is illustrated in Figs. 5 and 6. These plots show groupings by formation / soil type and specimen state, respectively. These figures also show, somewhat counter-intuitively, that the 'remoulded' data (mainly London Clay Formation) are more scattered than the 'undisturbed' (sample Gault5 has been omitted as it had an anomalous shrinkability index, Ψ of 20.1). It is notable that, whilst the liquidity index is often negative for undisturbed samples, the shrinkability index cannot be, as the specimen would have been untestable at an initial water content below the shrinkage limit.

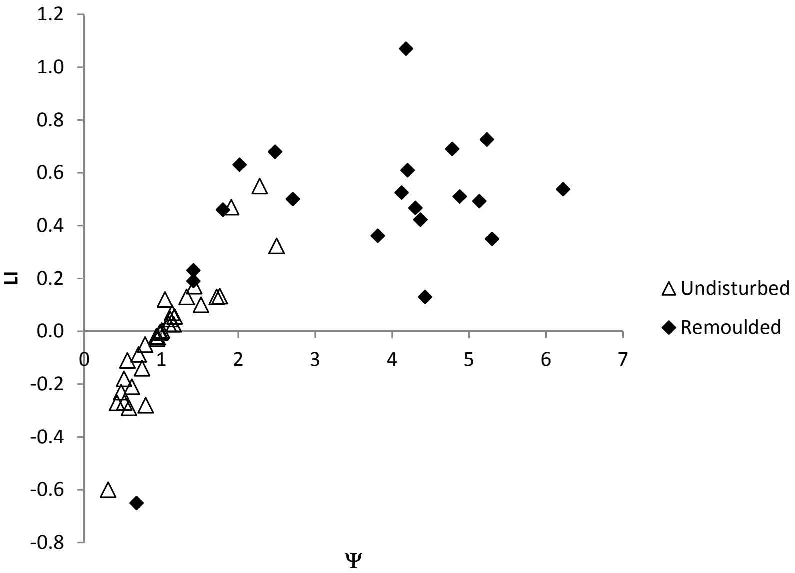

Fig. 6.

Density relationships

As pointed out by Garzonio & Sfalanga (2003) the shrinkage limit should, in theory, coincide with the peak of the bulk density curve. In practice this does appear to be the case, as described by Hobbs *et al*. (2014) and further demonstrated below. Relationships between water content and bulk density for selected undisturbed and remoulded SHRINKiT samples are shown in Figs. 7 and 8, respectively. These relationships resemble those for compaction tests, except that the latter use dry density. Water content at the peak bulk density achieved in the SHRINKiT test is observed to increase with reducing density. In general, the upper part of the ‘undisturbed’ plot (Fig. 7) is occupied by glacial tills the central part by Oxford and London Clay Formations (and other GB clays) and the lower part by tropical red and smectitic clays; the former plotting well below the GB soils. The ‘remoulded’ plot (Fig. 8) features more tightly packed curves particularly in the case of the London Clay Formation samples, though maintaining the distribution of Fig. 7. This is due to the greater degree of homogeneity associated with remoulded samples whereby all structural and most fabric features (present in the undisturbed samples) are removed.

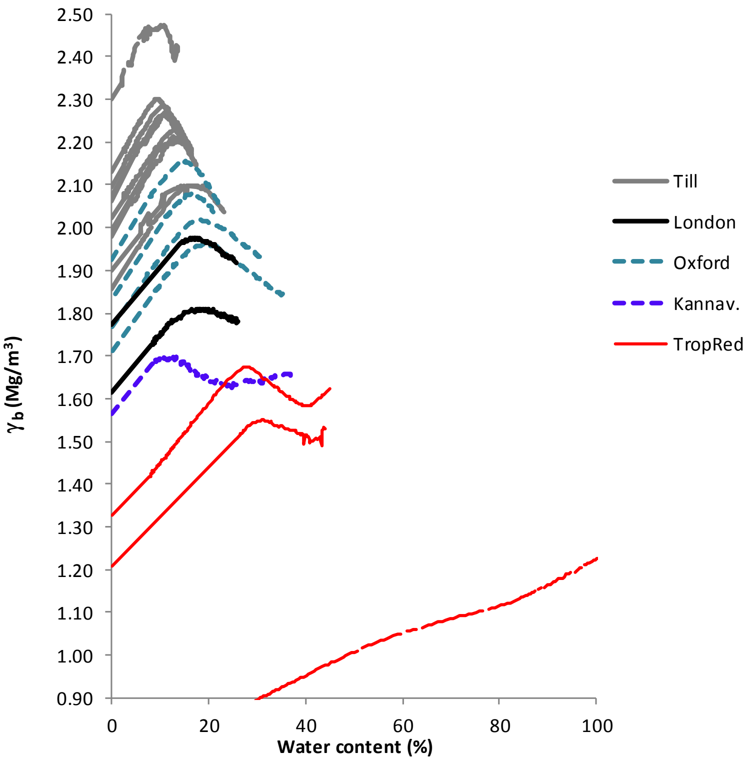

Fig. 7.

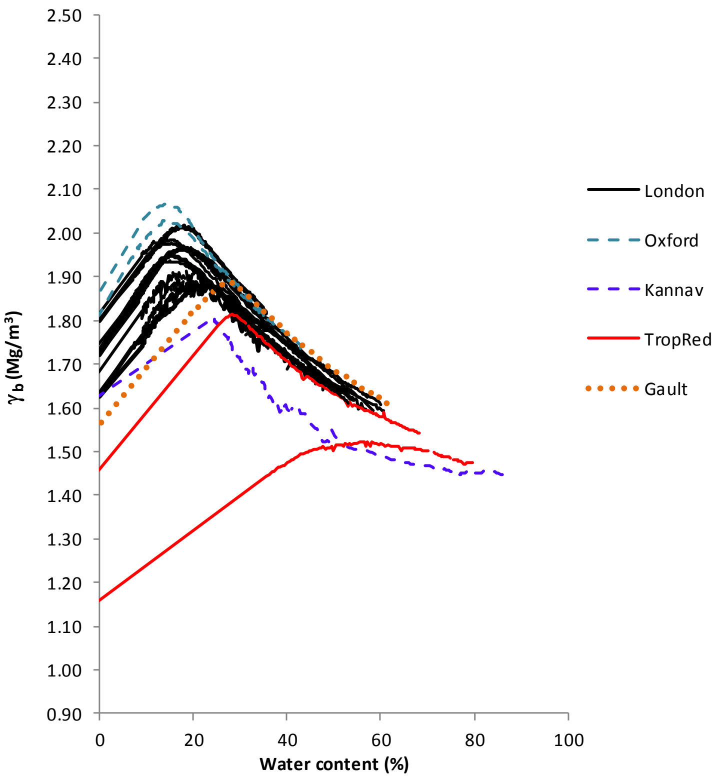

Fig. 8.

Specific examples where matched undisturbed/remoulded samples (refer to Table 2) have been tested are shown in Figs. 9 and 10. Here, the large density increases from the undisturbed to the remoulded state, for the tropical red clay soils, are shown, particularly for the andosols (TropRed 3 & 4). This compares with more modest density increases shown by the Oxford Clay and Kannaviou Formations. This behaviour is due to breakdown on remoulding of aggregated fabrics in the case of the Tropical Red samples (Fig. 9) and breakdown of structural features in the case of the Oxford Clay Formation and Kannaviou Formation samples (Fig. 10).

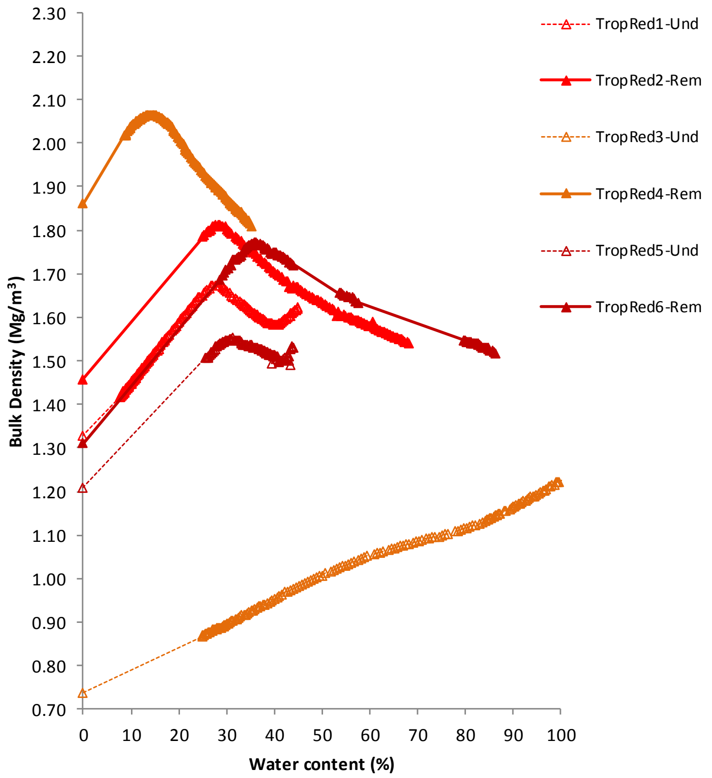

Fig. 9.

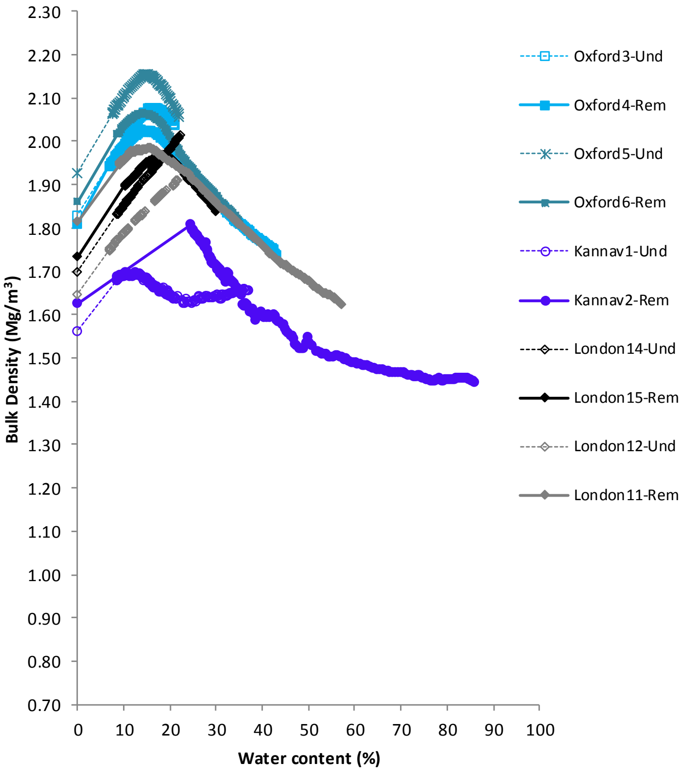

Fig. 10.

The coincidence of the shrinkage limit with the water content at the maximum bulk density achieved during the test has been referred to in Hobbs *et al*. (2014). The relationship is shown in Fig. 11. This might suggest that a 'peak bulk density' approach, determined from the SHRINKiT test, could serve as an alternative to the graphical construction employed by both BS1377 (BSI 1990) and SHRINKiT (Fig.1). However, some samples did not produce a peak bulk density during the test. These included Brickearth, Quick Clay, Ostend Member (a glaciolacustrine deposit) and Gault Formation samples, mainly undisturbed, which had either fractured badly during the test or had a high silt content. The reason for the maximum bulk density occurring at the shrinkage limit is that at this point in the shrinkage process the rate of volume loss is reducing before there is a significant reduction in weight loss rate. This is the point where desaturation of all pore sizes within the specimen is underway, which might also be connected to micro-cracking of clay peds contributing to the rapid slowing of volume reduction rate.

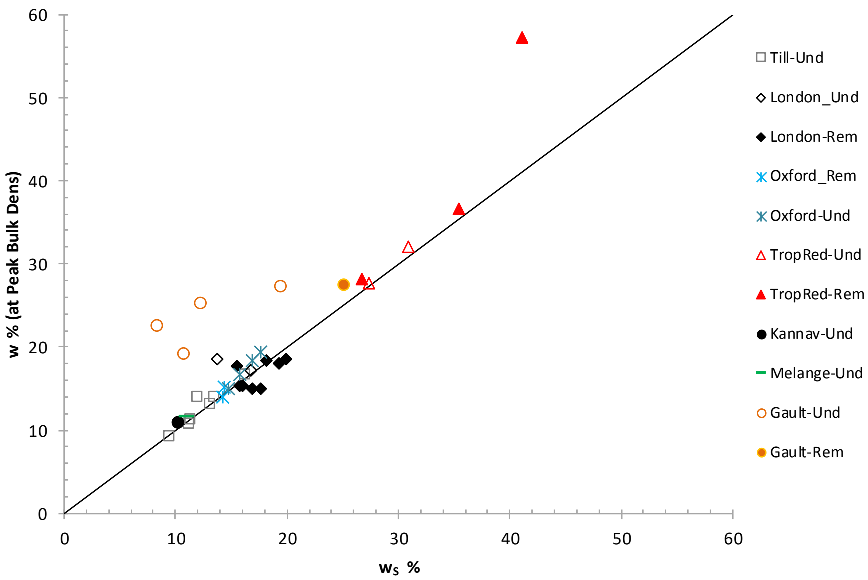

Fig. 11.

Suction relationships

As an adjunct to the shrinkage limit study, a small number of 'suction' measurements were made using a sub-1500 kPa ceramic plate extractor on remoulded shrinkage limit sub-samples. These confirm the relationship between bulk density and water content during shrinkage, discussed earlier, and introduce a relationship with suction, thus providing a three-dimensional 'characteristic curve' plot. An example for a remoulded London Clay Formation sample is shown in Fig. 12. The equivalent water content/bulk density/suction plot is shown in Fig. 13. This confirms the coincidence of peak bulk density (at 18.3% water content) with the shrinkage limit (18.2%) in this case.

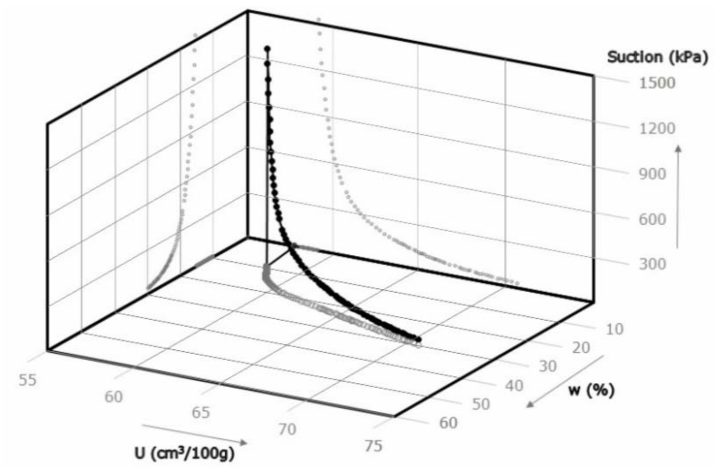

Fig. 12.

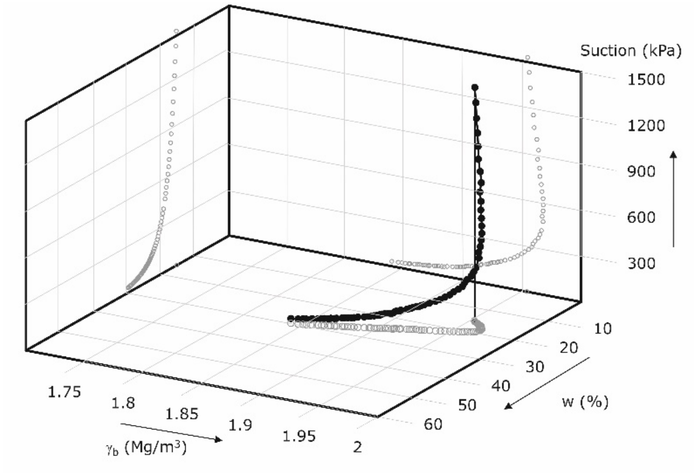

Fig. 13.

A comparative plot of the shrinkage limit derived from the SHRINKiT results using the graphical construction method shown in Fig. 1 and calculations taken from the ASTM method (refer to ‘Method’ section) and applied to the SHRINKiT data, is shown in Fig. 14, classified by formation and sample state.

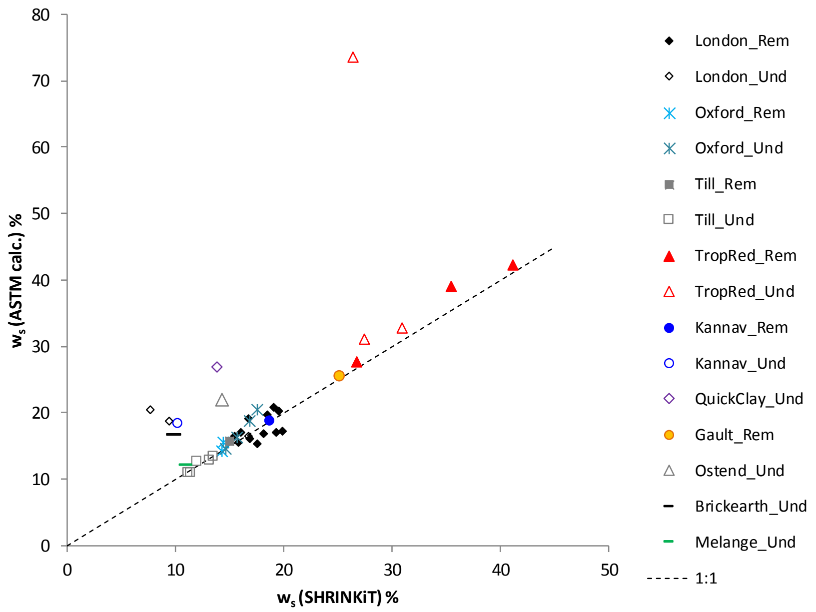

Fig. 14.

The plot shows a good agreement between remoulded samples of different types and formations. However, undisturbed samples generally show a poor agreement, albeit with exceptions, due to the lower degree of saturation and tend to have a non-linear AB line (Fig. 1). For example, the outlying undisturbed ‘TropRed’ sample in Fig. 14 has a particularly sinusoidal AB line in the SHRINKiT test plot which thus does not lend itself to the ASTM method.

Discussion

The results of laboratory tests to determine the shrinkage limit of fine-grained soils using an improved method, SHRINKiT and described in Hobbs *et al*. (2014), are reported and discussed. The method allows for a much greater number of measurement points during air drying than British Standard or other immersion methods and is capable of dealing with most weak, sensitive, metastable soils and undisturbed soils generally including those with structural weaknesses and silt/sand inclusions. A clear division between temperate soils and tropical soils, at least for those types tested, has been demonstrated whereby the latter have much higher shrinkage limits. The smectitic soils from Cyprus which were tested are intermediate between these. These factors are likely to be due to gross differences in soil fabric and clay mineralogy; an aspect which requires further research. Soils in the remoulded state have been shown to exhibit more uniform shrinkage behaviour compared with undisturbed with the exception of their shrinkability index relationships. This reflects their homogeneity.

The coincidence of the shrinkage limit with the water content at the peak bulk density achieved during the test has been observed for a majority of test. The reason for this is probably the progress of desaturation of the specimen during air drying, though its precise nature remains unclear. This relationship, and any departures from it, merit further research. The use of 'peak bulk density' as an alternative to the familiar shrinkage curve graphical construction (Fig. 1), in order to determine shrinkage limit, has been considered but does not apply to all the soils tested; as some did not produce a discernible peak bulk density during the test. It is suggested that this was due to fractures developing in the specimen during the test, leading to ambiguity in the measurement of volume, as was the case with several 'undisturbed' samples, particularly those from the Gault Formation. However, the problem of specimens fracturing during drying affects all shrinkage limit test methods.

The shrinkage limit results obtained by using the ASTM D4943-08 (ASTM 2008) calculation applied to the SHRINKiT data have demonstrated good agreement with the normal SHRINKiT result obtained by graphical construction (Fig.1) for remoulded, and some undisturbed, samples with high initial degrees of saturation. However, many undisturbed samples, typically with initial degrees of saturation less than 90%, showed poor agreement and also in many cases gave non-linear plots during the initial phase of shrinkage. To further this line of investigation, and with the introduction of a moisture extractor apparatus, a small number of three-dimensional 'water content/bulk density/suction' syntheses have been made and an example of London Clay Formation shown. This gives a form of enhanced 'soil characteristic curve' which potentially encapsulates the full nature of shrinkage behaviour. However, this has not yet been done on remoulded samples.

The factors that determine the outcome of shrinkage limit tests have been discussed by Sridharan & Prakash (1998) who state that plasticity (liquid limit and plasticity index) is a poor indicator, but that the grain size, 'packing' and fabric of the soil are determining factors. The results from the SHRINKiT tests described here, and in more detail in Hobbs *et al*. (2014), confirm this conclusion inasmuch as correlations with the other two Atterberg limits are generally poor, whereas the density relationships are indicative of a closer relationship between shrinkage limit and soil fabric. However, the influence of clay mineralogy and plasticity reveals itself in the development, or otherwise, of fractures during the test; the latter also being affected by drying rate. It is interesting to note, in the light of the above comments, and those of Sridharan &

Prakash (1998), that plasticity, specifically plasticity index, is frequently (and incorrectly) used in the foundation engineering and building industries as a surrogate for the direct measurement of shrinkage.

Based on the shrinkage limit test results described in this paper and in Hobbs *et al*., (2014) a proposed classification for the shrinkage limit of remoulded samples is shown in Table 4. Using this classification, all remoulded GB clays fall within the 'low' to 'high' classes with the exception of the Gault Formation sample (Gault5) which is 'very high'. The London Clay Formation samples tested lie within the 'high' class while the tropical red clays tested lie within the 'very high' and 'extremely high' classes. The Oxford Clay Formation and Till samples tested lie within the 'medium' class.

Table 4. *Proposed classification for shrinkage limit, w_s (remoulded samples only)*

w_s (%)	Class description
<10	Low
10 - 15	Medium
15 - 20	High
20 - 30	Very high
>30	Extremely high

It is proposed that such a classification, in this case based on shrinkage limit, particularly in relation to the in situ water content, would be more useful than those traditionally used by the building and construction industries based solely on plasticity index. A pragmatic approach would be to provide both shrinkage index and plasticity index data, thus giving the full range of water content behaviour across the Atterberg indices. The SHRINKiT test has the capability to provide extra information for industry in terms of measured volumetric strains and shrinkage anisotropy for undisturbed clay formations and derived compacted fill materials alike. The influence of structural and fabric features, such as joints and inclusions, found in the natural soil, is accounted for in this test method.

Conclusions

The SHRINKiT method provides an alternative to the current BS methods and equivalent mercury immersion and wax coating methods and benefits from greater accuracy, safety and scope for research. Its applicability across a wide range of shrinkage behaviour has been demonstrated from British to tropical clay soils. Some basic relationships have been shown, for example with the shrinkage equivalents of plasticity and liquidity indices. The significance of the shrinkage limit and its sensitivity to undisturbed and remoulded sample states has been explored where matched samples were available. The use of water content at peak bulk density in the SHRINKiT test as a proxy for shrinkage limit (from graphical construction) has been indicated (with reservation) and the combining of shrinkage and suction data has also been demonstrated for remoulded samples. The SHRINKiT method, in common with other methods, performs poorly where the test specimen suffers major fractures during the test; the latter probably a function of plasticity, clay mineralogy and drying rate.

Improved knowledge of the shrinkage behaviour of fine-grained soils can only benefit engineering and building practice, particularly where soils with high clay content and active clay minerals are involved. The range of water contents over which volume change occurs, based on laboratory tests, is a useful predictive tool for subsidence and heave in foundations and as a factor in geohazard assessment generally. To that end, a soil classification for shrinkage limit has been put forward.

The SHRINKiT method has the flexibility to test a wide variety of soil types and specimen states, some of which would be untestable by other standard or established methods. The shrinkage limit, as an Atterberg limit sensu strictu, should logically be applicable only to remoulded samples, the work with undisturbed samples described here provides additional insight into the true shrinkage behaviour of natural clay materials in the field and the reasons for departures from the behaviour measured with remoulded samples in laboratory tests and encountered in the use of engineered clay fills. Ideally, both sample states should be tested and the shrinkage sensitivity determined.

Fig. 1. Schematic plot of water content vs. volume showing graphical construction to determine shrinkage limit (dashed lines), and other Atterberg Limits. w_S, Shrinkage limit; w_P, Plastic limit; w_L, Liquid limit; I_S, Shrinkage index; I_P, Plasticity index.
Fig. 2. Water content vs. Volume per 100g dry soil, U for selected samples (SHRINKiT test) of GB soils by Formation / soil type
Fig. 3. Water content vs. Volume per 100g dry soil, U for selected samples (SHRINKiT test) of non-GB soils by Formation / soil type.
Fig. 4. Envelopes of Water content vs. Volume per 100g dry soil, U for all data (SHRINKiT test).
Fig. 5. Shrinkability index vs. Liquidity index for all data (by formation / soil type); sample GAULT5 omitted for clarity; Und, Undisturbed; Rem, Remoulded
Fig. 6. Shrinkability index vs. Liquidity index for all data (by sample state).
Fig. 7. Water content vs. Bulk density, selected data, by formation / soil type (undisturbed samples only).
Fig. 8. Water content vs. Bulk density, selected data, by formation / soil type (remoulded samples only).
Fig. 9. Water content vs. Bulk density, tropical red clay soils (matched undisturbed/remoulded samples, refer to Table 2); Und, Undisturbed; Rem, Remoulded.
Fig. 10. Water content vs. Bulk density, selected GB & Cyprus data, by formation (matched undisturbed/remoulded samples, refer to Table 2); Und, Undisturbed; Rem, Remoulded.
Fig. 11. Shrinkage limit, vs. Water content at peak bulk density by formation/soil type and sample state (line shows 1:1 relationship); Und, Undisturbed; Rem, Remoulded.
Fig. 12. Three-axis plot of Water content vs. Unit volume vs. Suction for sample LONDON15
Fig. 13. Three-axis plot of Water content vs. Bulk density vs. Suction for sample LONDON15
Fig. 14. Shrinkage limit (SHRINKiT: graphical construction), vs. Shrinkage limit (SHRINKiT: ASTM calculation) by formation/soil type and state (dashed line, 1:1 relationship); Und, Undisturbed; Rem, Remoulded.

Notation

G_S	Specific gravity
I_P	Plasticity index ($= w_L - w_P$)
I_S	Shrinkage index ($= w_P - w_S$)
L_S	Linear shrinkage
Rem	Remoulded sample
R_S	Shrinkage ratio
S_{n0}	Degree of saturation at start of test
w_0	Water content at start of test
w_L	Liquid limit
w_P	Plastic limit
w_S	Shrinkage limit
LI	Liquidity index ($= (w_0 - w_p)/I_p)$)
Ψ	Shrinkability index ($= (w_0 - w_S)/I_S)$)
ΔV_{tot}	Volumetric strain (total volume reduction during test, *dependent on w_0*)
U	Unit volume (volume per 100 g dry soil)
Und	Undisturbed sample

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