

# 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.

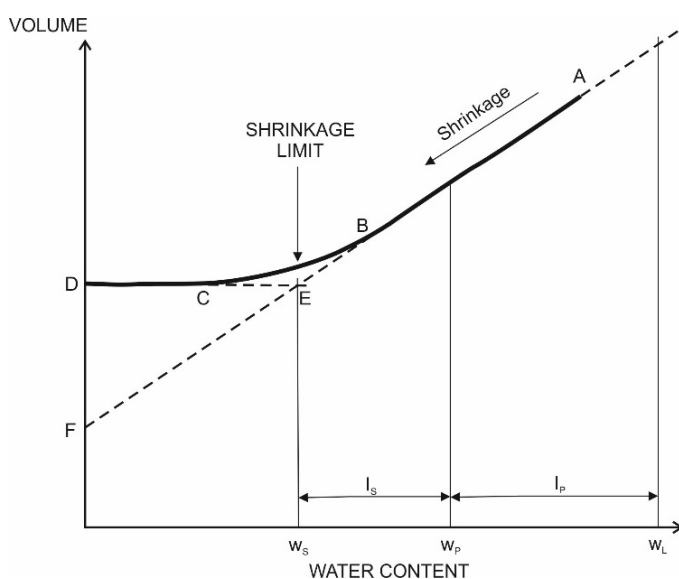


Fig. 1.

The shrinkage limit was one of seven state limits originally conceived by Albert Atterberg (Atterberg,

38 1911a, 1911b) and further described by Casagrande (1948) and one of three that are currently covered by  
39 test standards (e.g. BSI 1990, ASTM 2018). The shrinkage limit of fine soil ( $w_s$ ) is conceptually defined  
40 as the water content at which the phase of the soil changes from the 'semi-solid' to the 'solid' state  
41 (Sridharan & Prakash 1998). This is graphically illustrated in Fig. 1 where continuous reduction in water  
42 content results in no further volume change. The shrinkage from A to B is where volume reduction  
43 matches water loss. The gradient of the line AB is the initial degree of saturation,  $S_n$  if volume change is  
44 expressed as voids ratio and, if volume change is expressed as a percentage of dry volume, equals the  
45 shrinkage ratio,  $R_s$ . Point D is the oven dried state (105°C) and point E defines the shrinkage limit (BSI  
46 1990) at the graphical intercept of lines AB and CD. Point B, usually referred to as the air-entry point  
47 (Haigh *et al.* 2013), represents the water content at which water loss outstrips volume reduction and the  
48 degree of saturation starts to reduce significantly. The shrinkage limit also coincides with the point of  
49 peak bulk density achieved during the test (discussed later).

50  
51 The two British Standard methods for measuring shrinkage limit directly employ Archimedes principle  
52 applied to a mercury bath in order to determine the volume of the specimen, BS 1377-2, tests 6.3 and 6.4  
53 (BSI 1990). Both methods use mercury and, therefore, have health and safety risks associated with them,  
54 including the disposal of the contaminated sample. Whilst the Standard does not specify that the tests  
55 should be just be on remoulded samples (as for the other Atterberg limits - liquid and plastic limits), the  
56 intention is implicit. However, there is no technical reason why undisturbed samples cannot be used and,  
57 undisturbed samples, in addition to remoulded samples, have been used in this study. Also, the results on  
58 undisturbed samples might have more application for engineering purposes. The Standard method uses a  
59 mercury cell originally developed by the Transport Research Laboratory, TRL (Road Research Laboratory  
60 1952; Ackroyd 1969). The 'subsidiary' method, based on American Society for Testing & Materials  
61 (ASTM) and American Association of State Highway & Transportation Officials (AASHTO) methods  
62 (D427-04 and T92-97, respectively; ASTM 2007) and utilised worldwide (e.g. Mishra & Sridharan 2017),  
63 also uses mercury immersion and the same graphical construction. Other methods based on 'coated-clod'  
64 specimens have been used: employing immersion (ASTM 2008; Sridharan & Prakash 2009), laser  
65 scanning (Rossi *et al.* 2008) and optical scanning (Sander & Gerke 2007; Stewart *et al.* 2012). The current  
66 ASTM method (D4943-08) employs a hot wax coating Archimedes immersion technique where shrinkage  
67 limit is calculated solely from the initial and oven-dried states (ASTM 2008). This type of immersion  
68 method is destructive, unlike the scanning methods, and assumes that the initial specimen is remoulded  
69 and fully saturated and that the line AB in Fig. 1 is straight. Whilst the shrinkage limit is mentioned in  
70 current Eurocode 7 documents, the methods of testing are not described.

71  
72 A new automated laboratory test apparatus for the determination of shrinkage limit, entitled SHRINKiT,  
73 was developed to provide a safer and more accurate method than those previously available and to promote  
74 the use of an important but under-utilised test. This, along with a preliminary data set, was described in  
75 Hobbs *et al.* (2010). The fundamental aspects of shrinkage behaviour were further examined by Hobbs *et al.*  
76 *et al.* (2014) using the 'SHRINKiT' method of testing which was validated using a limited preliminary data  
77 set. The method employs a simple form of laser scanner and a digital balance to measure volume and  
78 weight, respectively. A large number of volume and weight measurements are made over a period of  
79 several days while the specimen air-dries. Cylindrical specimens (nominally 100 x 100 mm) taken from  
80 remoulded or undisturbed samples are used; the latter prepared from class 1, undisturbed samples (BSI,  
81 2015) prepared by hand trimming in trial pits or from rotary drilled core and preserved to ensure no or  
82 minimal water loss,.

## 83 84 **Method**

85  
86 The shrinkage limit tests were carried out in the laboratory using the BGS's computer automated SHRINKiT  
87 method (Hobbs *et al.* 2014; Hobbs *et al.* 2010). This measures specimen mass and volume simultaneously,

88 the former with an integral digital balance to 0.01g and the latter using a travelling laser rangefinder and  
89 rotating specimen platform which combine to act as a scanner. This enables a large number of readings  
90 per test that is used to definite the volume-water content plot to air dried and of the oven dried sample,  
91 and the graphical construction to determine shrinkage limit (Fig. 1). A single cylindrical specimen (100 x  
92 100 mm) taken from a remoulded or undisturbed sample is used (10% larger or smaller specimens can be  
93 accommodated). The apparatus is calibrated using plain and contoured aluminium cylinders of known  
94 weight and volume. Average errors of 0.015 % and 0.07 % were obtained for weight and volume,  
95 respectively, using five different calibration cylinders, and the software version (v2.5.2) and the laser  
96 point density (300 per scan) used during the tests described here. The calculation used in the ASTM test  
97 D4943-08 ‘wax’ method (ASTM 2008) when applied to the SHRINKiT data allowed a comparison to be  
98 made with the SHRINKiT results. The other soils index tests were carried out according to BS1377 (BSI:  
99 1990, Part 5). The ‘suction’ tests were carried out using a Soil Moisture Equipment Corporation 1500F1  
100 (1500 kPa capacity) ceramic plate extractor on a selection of remoulded shrinkage limit sub-samples at  
101 water contents close to their liquid limit. Seven stages were carried out from 100 to 1500 kPa and a best-  
102 fit curve applied. All tests were conducted in the laboratory at a constant 20°C.

103  
104 As described earlier, the ASTM method (ASTM 2008) employs an Archimedes immersion technique  
105 applied to a disc-shaped specimen of remoulded soil, first air-dried, then oven-dried and coated in hot  
106 wax. The calculation employed assumes that the initial degree of saturation is 100% and that the initial  
107 condition (Point A in Fig. 1) falls on a straight line through Point E (Fig. 1). In addition to the normal  
108 graphical construction (Fig. 1), the final calculation from D4943-08 has been applied to the SHRINKiT data  
109 using the following formula:

$$w_s = w_0 - \left[ \frac{(V_0 - V_d)\rho_w}{m_s} \right] \times 100 \quad (1)$$

110  
111 where  $w_s$ , Shrinkage limit;  $w_0$ , Initial water content;  $V_0$ , Initial volume;  $V_d$ , Oven dry volume;  $\rho_w$ , Density  
112 of water;  $m_s$ , Oven dry mass.

## 113 114 **Samples**

### 115 **Undisturbed**

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

### 124 **Remoulded**

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

## 133 134 **Results**

135  
136

137 Following the preliminary set of test results described in Hobbs *et al.* (2014), a further thirty-two tests  
 138 were carried out using the SHRINKiT apparatus, details and results for which are tabulated in Table 1 and  
 139 Table 2, and plots for selected tests illustrated in Figs. 2 and 3. Shrinkage limits ranged from 14.3 to 41.1  
 140 % for remoulded samples and 7.7 to 30.9 % for undisturbed samples. Volumetric strains (dependent on  
 141 initial water content,  $w_0$ ) ranged from 2 to 23 % for undisturbed samples and from 18 to 52 % for  
 142 remoulded samples. Formations and soil types are seen to occupy discrete zones within Fig. 4, notably  
 143 the large zone for undisturbed tropical red clay which, though not populated, may indicate the possible  
 144 range for such soils as allophanic andosols which, in their undisturbed state, have aggregated and  
 145 metastable fabrics. Abbreviations for test parameters are explained under ‘Notation’. Interruptions in plots  
 146 are due to technical issues during tests.

147

148 **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)	<i>Ferralsol</i> (Older Quaternary Volcanics)	786950, 274200
TropRed2	Subang, Java, Indonesia (Pit 12, 3.0 m)	<i>Ferralsol</i> (Older Quaternary Volcanics)	786950, 274200
TropRed3	Lembang, Java, Indonesia (Pit 11, 5.0 m)	<i>Andosol</i> (Younger Quaternary Volcanics)	786950, 246400
TropRed4	Lembang, Java, Indonesia (Pit 11, 5.0 m)	<i>Andosol</i> (Younger Quaternary Volcanics)	786950, 246400
TropRed5	Subang, Java, Indonesia (Pit 12, 5.0 m)	<i>Ferralsol</i> (Older Quaternary Volcanics)	786950, 274200
TropRed6	Subang, Java, Indonesia (Pit 12, 5.0 m)	<i>Ferralsol</i> (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

149 \* Sample provided by Norwegian Geotechnical Institute (NGI);

150 NGR, National Grid Reference for the country of sample origin,

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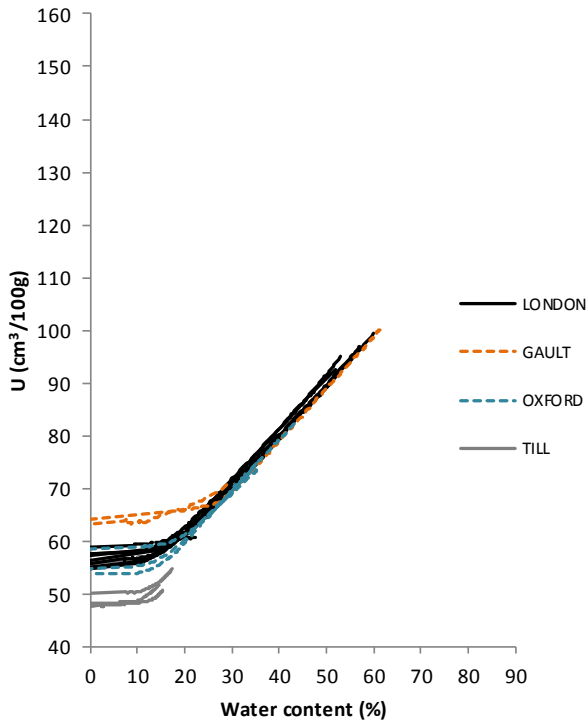
154 **Table 2. Results of shrinkage limit (SHRINKiT) test and other index tests**

Sample	State	w <sub>s</sub> (%)	w <sub>L</sub> (%)	I <sub>p</sub> (%)	R <sub>s</sub> (Mg/m <sup>3</sup> )	w <sub>0</sub> (%)	S <sub>a0</sub> (%)	ΔV <sub>tot</sub> (%)	I <sub>s</sub> (%)	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

155 \* † indicate matched undisturbed/remoulded samples; Und, Undisturbed; Rem, Remoulded.

156 Refer to 'Notation' section for geotechnical parameter abbreviations.

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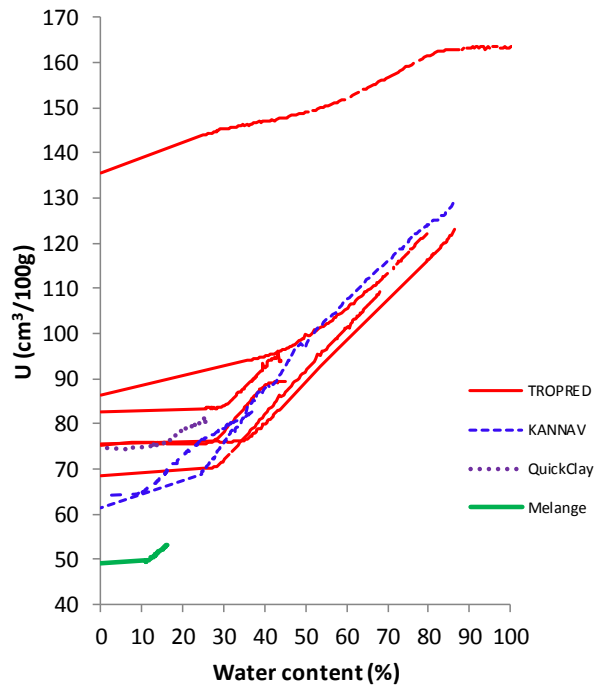
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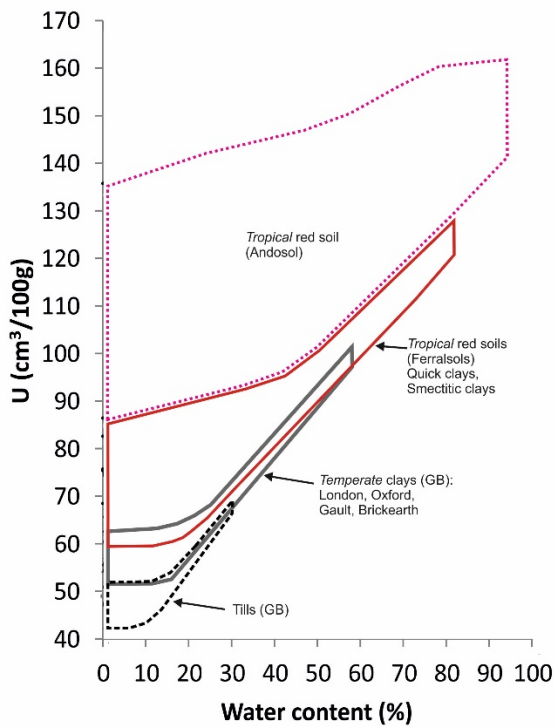
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**Fig. 2.**



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163 **Fig. 3.**  
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166  
167 **Fig. 4.**

168

### 169 *Shrinkage sensitivity*

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

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

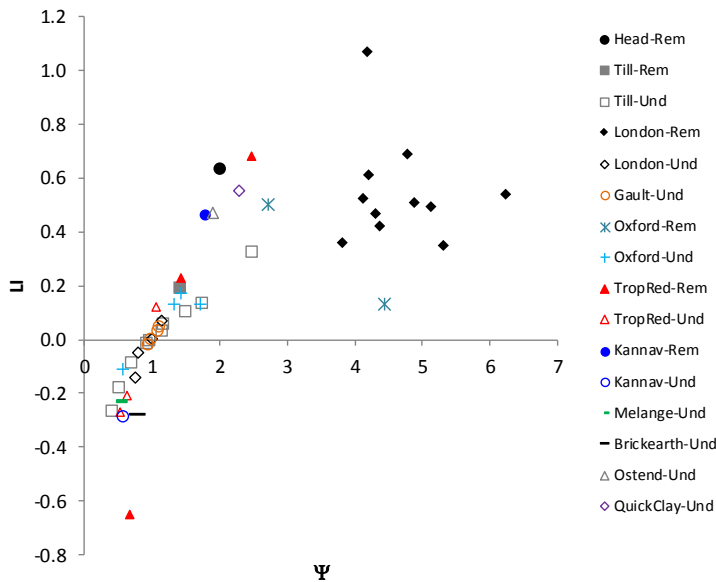
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**Table 3.** Shrinkage limit sensitivities for ‘matched’ undisturbed and remoulded samples

Samples	$w_s$	$w_s$	Sensitivity
	(Und) %	(Rem) %	
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

180  
 181  
 182  
 183

Und, Undisturbed; Rem, Remoulded



184  
 185

**Fig. 5.**

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187 The shrinkability index,  $\Psi$  is defined in equation 2:

188

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

189

where  $w_0$ , initial water content;

190

$w_s$ , shrinkage limit;

191

$I_s$ , shrinkage index (equation (3)).

192

$$I_s = w_p - w_s \quad (3)$$

193

194

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

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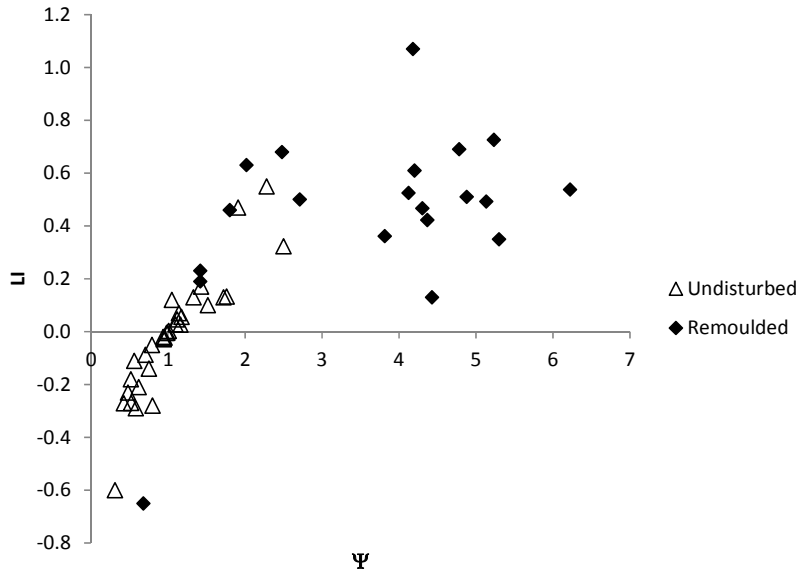
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201 as it had an anomalous shrinkability index,  $\Psi$  of 20.1). It is notable that, whilst the  
 202 liquidity index is often negative for undisturbed samples, the shrinkability index cannot  
 203 be, as the specimen would have been untestable at an initial water content below the  
 204 shrinkage limit.

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206

207 **Fig. 6.**

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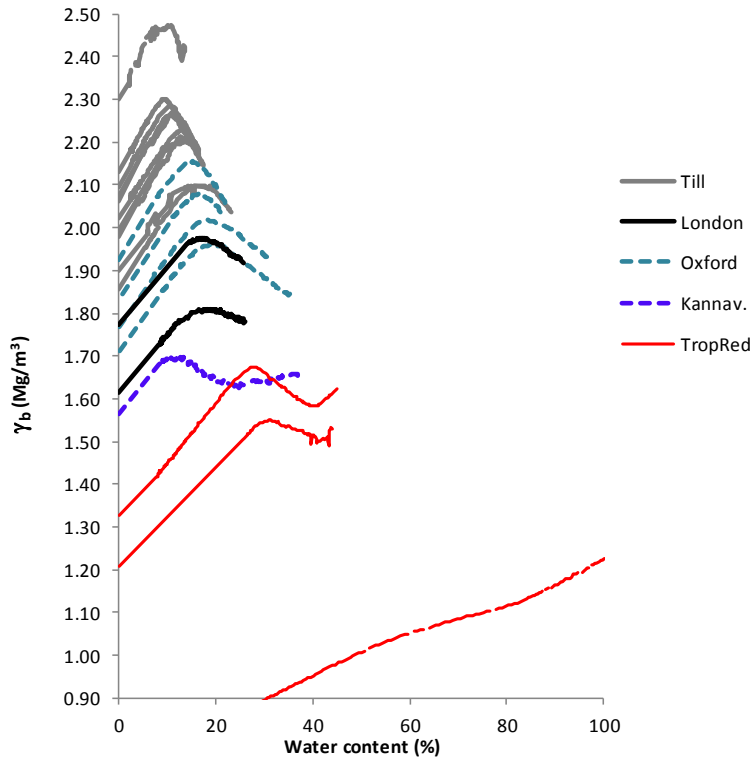
209 ***Density relationships***

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

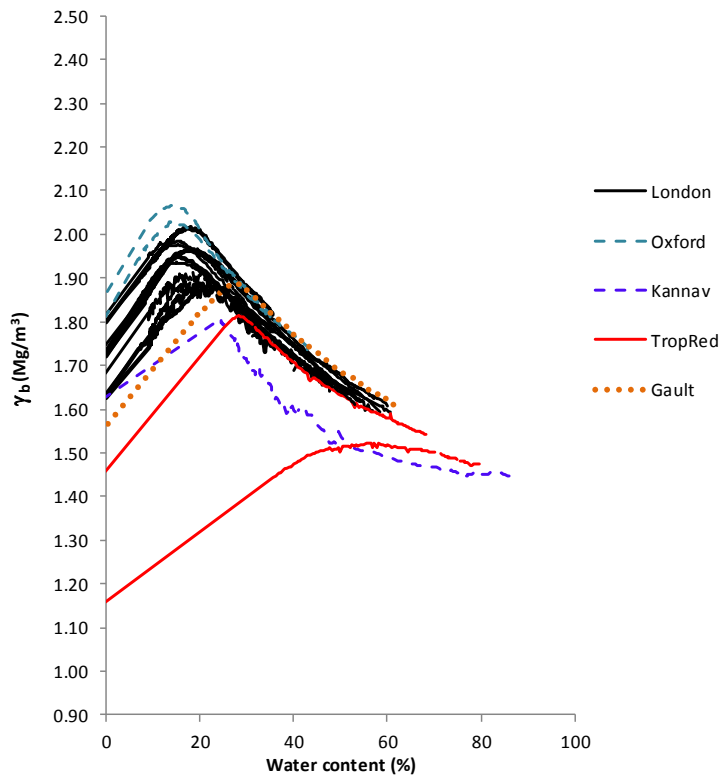
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Fig. 7.



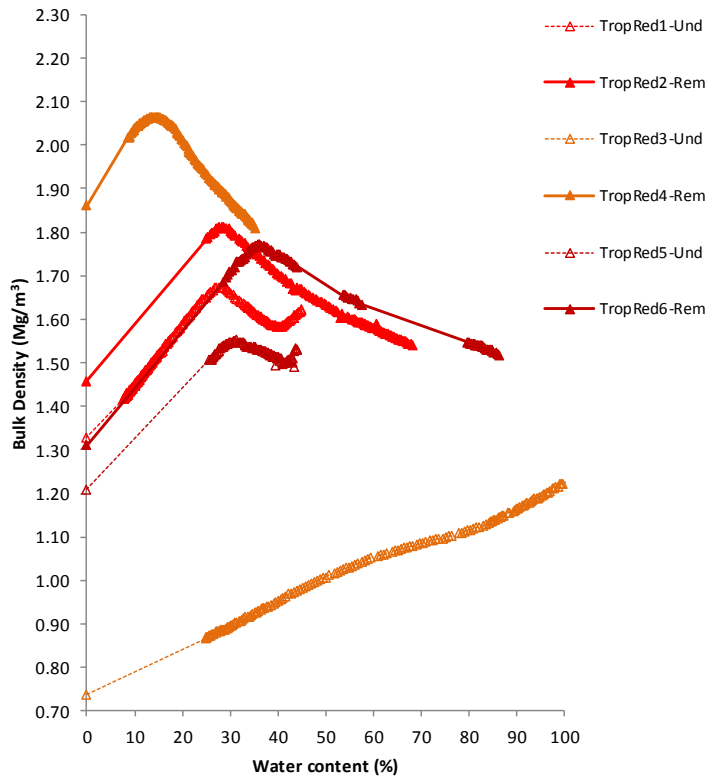
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Fig. 8.

233 Specific examples where matched undisturbed/remoulded samples (refer to Table 2)  
234 have been tested are shown in Figs. 9 and 10. Here, the large density increases from the  
235 undisturbed to the remoulded state, for the tropical red clay soils, are shown,  
236 particularly for the andosols (TropRed 3 & 4). This compares with more modest density

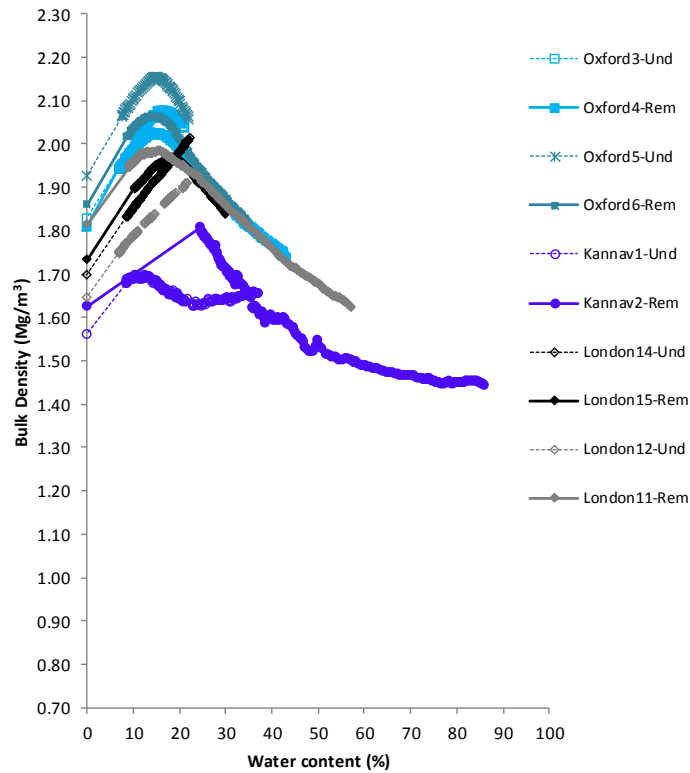
237 increases shown by the Oxford Clay and Kannaviou Formations. This behaviour is due  
238 to breakdown on remoulding of aggregated fabrics in the case of the Tropical Red  
239 samples (Fig. 9) and breakdown of structural features in the case of the Oxford Clay  
240 Formation and Kannaviou Formation samples (Fig. 10).

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**Fig. 9.**



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247

**Fig. 10.**

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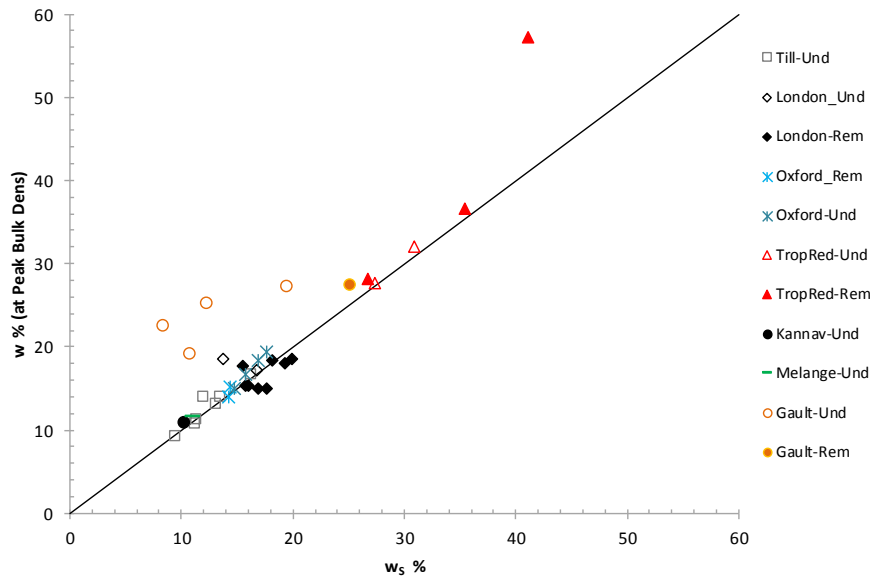
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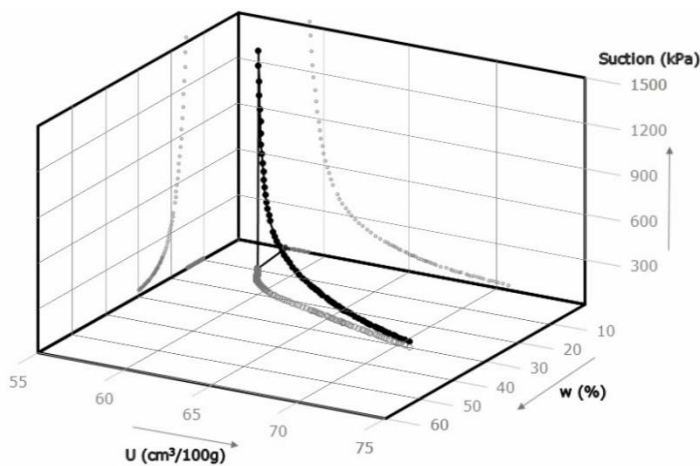
The coincidence of the shrinkage limit with the water content at the maximum bulk density achieved during the test has been referred to in Hobbs *et al.* (2014). The relationship is shown in Fig. 11. This might suggest that a ‘peak bulk density’ approach, determined from the SHRINKiT test, could serve 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 pedes contributing to the rapid slowing of volume reduction rate.



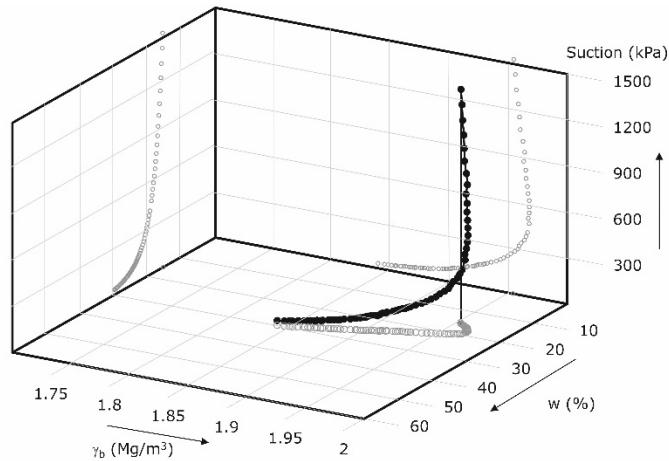
264  
265 **Fig. 11.**

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267 ***Suction relationships***

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269 As an adjunct to the shrinkage limit study, a small number of ‘suction’ measurements  
270 were made using a sub-1500 kPa ceramic plate extractor on remoulded shrinkage limit  
271 sub-samples. These confirm the relationship between bulk density and water content  
272 during shrinkage, discussed earlier, and introduce a relationship with suction, thus  
273 providing a three-dimensional ‘characteristic curve’ plot. An example for a remoulded  
274 London Clay Formation sample is shown in Fig. 12. The equivalent water content/bulk  
275 density/suction plot is shown in Fig. 13. This confirms the coincidence of peak bulk  
276 density (at 18.3% water content) with the shrinkage limit (18.2%) in this case.  
277



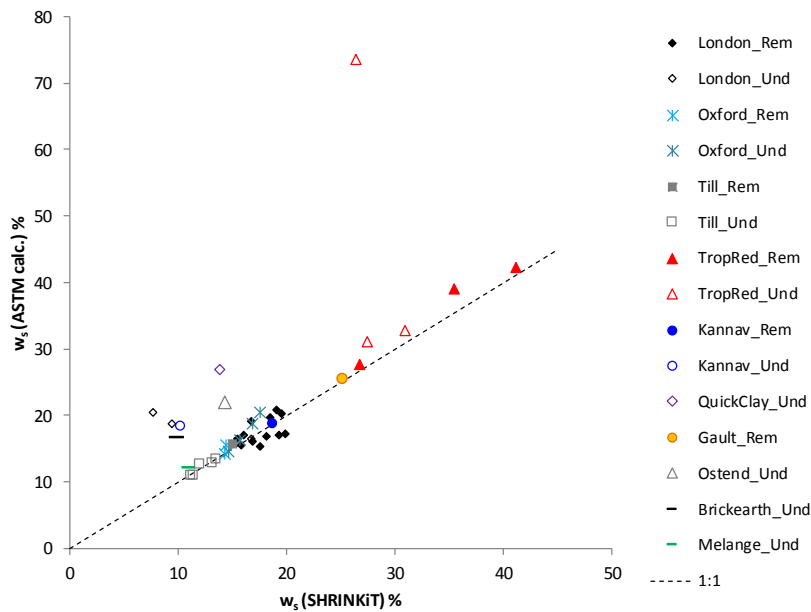
278  
279 **Fig. 12.**  
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**Fig. 13.**

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.



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**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

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

317  
318 The coincidence of the shrinkage limit with the water content at the peak bulk density  
319 achieved during the test has been observed for a majority of test. The reason for this is  
320 probably the progress of desaturation of the specimen during air drying, though its  
321 precise nature remains unclear. This relationship, and any departures from it, merit  
322 further research. The use of ‘peak bulk density’ as an alternative to the familiar  
323 shrinkage curve graphical construction (Fig. 1), in order to determine shrinkage limit,  
324 has been considered but does not apply to all the soils tested; as some did not produce  
325 a discernible peak bulk density during the test. It is suggested that this was due to  
326 fractures developing in the specimen during the test, leading to ambiguity in the  
327 measurement of volume, as was the case with several ‘undisturbed’ samples,  
328 particularly those from the Gault Formation. However, the problem of specimens  
329 fracturing during drying affects all shrinkage limit test methods.

330  
331 The shrinkage limit results obtained by using the ASTM D4943-08 (ASTM 2008)  
332 calculation applied to the SHRINKiT data have demonstrated good agreement with the  
333 normal SHRINKiT result obtained by graphical construction (Fig.1) for remoulded, and  
334 some undisturbed, samples with high initial degrees of saturation. However, many  
335 undisturbed samples, typically with initial degrees of saturation less than 90%, showed  
336 poor agreement and also in many cases gave non-linear plots during the initial phase of  
337 shrinkage. To further this line of investigation, and with the introduction of a moisture  
338 extractor apparatus, a small number of three-dimensional ‘water content/bulk  
339 density/suction’ syntheses have been made and an example of London Clay Formation  
340 shown. This gives a form of enhanced ‘soil characteristic curve’ which potentially  
341 encapsulates the full nature of shrinkage behaviour. However, this has not yet been  
342 done on remoulded samples.

343  
344 The factors that determine the outcome of shrinkage limit tests have been discussed by  
345 Sridharan & Prakash (1998) who state that plasticity (liquid limit and plasticity index)  
346 is a poor indicator, but that the grain size, ‘packing’ and fabric of the soil are  
347 determining factors. The results from the SHRINKiT tests described here, and in more  
348 detail in Hobbs *et al.* (2014), confirm this conclusion inasmuch as correlations with the  
349 other two Atterberg limits are generally poor, whereas the density relationships are  
350 indicative of a closer relationship between shrinkage limit and soil fabric. However, the  
351 influence of clay mineralogy and plasticity reveals itself in the development, or  
352 otherwise, of fractures during the test; the latter also being affected by drying rate. It is  
353 interesting to note, in the light of the above comments, and those of Sridharan &

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

357

358 Based on the shrinkage limit test results described in this paper and in Hobbs *et al.*,  
359 (2014) a proposed classification for the shrinkage limit of remoulded samples is shown  
360 in Table 4. Using this classification, all remoulded GB clays fall within the ‘low’ to  
361 ‘high’ classes with the exception of the Gault Formation sample (Gault5) which is ‘very  
362 high’. The London Clay Formation samples tested lie within the ‘high’ class while the  
363 tropical red clays tested lie within the ‘very high’ and ‘extremely high’ classes. The  
364 Oxford Clay Formation and Till samples tested lie within the ‘medium’ class.

365

366 **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

367

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

378

## 379 **Conclusions**

380

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

394

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

400 soil classification for shrinkage limit has been put forward.

401

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

411

412 **Fig. 1.** Schematic plot of water content vs. volume showing graphical construction to determine  
413 shrinkage limit (dashed lines), and other Atterberg Limits.  $w_S$ , Shrinkage limit;  $w_P$ , Plastic limit;  $w_L$ ,  
414 Liquid limit;  $I_S$ , Shrinkage index;  $I_P$ , Plasticity index.

415 **Fig. 2.** Water content vs. Volume per 100g dry soil, U for selected samples (SHRINKiT test) of GB  
416 soils by Formation / soil type

417 **Fig. 3.** Water content vs. Volume per 100g dry soil, U for selected samples (SHRINKiT test) of non-  
418 GB soils by Formation / soil type.

419 **Fig. 4.** Envelopes of Water content vs. Volume per 100g dry soil, U for all data (SHRINKiT test).

420 **Fig. 5.** Shrinkability index vs. Liquidity index for all data (by formation / soil type); sample GAULT5  
421 omitted for clarity; Und, Undisturbed; Rem, Remoulded

422 **Fig. 6.** Shrinkability index vs. Liquidity index for all data (by sample state).

423 **Fig. 7.** Water content vs. Bulk density, selected data, by formation / soil type (undisturbed samples only).

424 **Fig. 8.** Water content vs. Bulk density, selected data, by formation / soil type (remoulded samples only).

425 **Fig. 9.** Water content vs. Bulk density, tropical red clay soils (matched undisturbed/remoulded samples,  
426 refer to Table 2); Und, Undisturbed; Rem, Remoulded.

427 **Fig. 10.** Water content vs. Bulk density, selected GB & Cyprus data, by formation (matched  
428 undisturbed/remoulded samples, refer to Table 2); Und, Undisturbed; Rem, Remoulded.

429 **Fig. 11.** Shrinkage limit, vs. Water content at peak bulk density by formation/soil type and sample state  
430 (line shows 1:1 relationship); Und, Undisturbed; Rem, Remoulded.

431 **Fig. 12.** Three-axis plot of Water content vs. Unit volume vs. Suction for sample LONDON15

432 **Fig. 13.** Three-axis plot of Water content vs. Bulk density vs. Suction for sample LONDON15

433 **Fig. 14.** Shrinkage limit (SHRINKiT: graphical construction), vs. Shrinkage limit (SHRINKiT: ASTM  
434 calculation) by formation/soil type and state (dashed line, 1:1 relationship); Und, Undisturbed; Rem,  
435 Remoulded.

436

437

## 438 Notation

439

440  $G_S$  Specific gravity

441  $I_P$  Plasticity index ( $= w_L - w_P$ )

442  $I_S$  Shrinkage index ( $= w_P - w_S$ )

443  $L_S$  Linear shrinkage

444 Rem Remoulded sample

445  $R_S$  Shrinkage ratio

446  $S_{n0}$  Degree of saturation at start of test

447  $w_0$  Water content at start of test

448  $w_L$  Liquid limit

449  $w_P$  Plastic limit

450  $w_S$  Shrinkage limit

451 LI Liquidity index ( $= (w_0 - w_P) / I_P$ )

452  $\Psi$  Shrinkability index ( $= (w_0 - w_S) / I_S$ )

453  $\Delta V_{tot}$  Volumetric strain (total volume reduction during test, *dependent on  $w_0$* )

454 U Unit volume (volume per 100 g dry soil)

455 Und Undisturbed sample

456



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458

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463

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