Use of Fall Cones to Determine Atterberg Limits: A Review

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ABSTRACT

This paper reviews the percussion-cup liquid limit (*LL*), thread-rolling plastic limit (*PL*), and various fall-cone and other approaches employed for consistency limit determinations on fine soil, highlighting their use and misuse for soil classification purposes and in existing correlations. Since the *PL* does not correspond to a unique value of remoulded undrained strength, there is no scientific reason why plastic limit measurements obtained using the thread-rolling and strength-based fall cone or extrusion methods should coincide. Various correlations are established relating *LL* values deduced using the percussion-cup and fall-cone approaches. The significance of differences in the strain-rate dependency on the mobilised fall-cone strength is reviewed. The paper concludes with recommendations on the standardisation of international codes and the wider used of the fall-cone approach for soft to medium stiff clays in establishing the strength variability with changing water content and further index parameters.

Keywords: Atterberg Limits; Consistency Limits; Liquid Limit; Plastic Limit; Measurement; Review

INTRODUCTION

The liquid limit (*LL*) and plastic limit (*PL*) tests are among the most commonly specified tests in the geotechnical engineering industry and originate from the original research of Atterberg (1911a, 1911b), which was subsequently standardised for use in civil engineering applications by Terzaghi (1926a, 1926b) and Casagrande (1932, 1958) and adopted for the classification of fine-grained soils. These Atterberg limits have been used for numerous purposes, including: to estimate strength, deformation and critical-state soil mechanics parameters (e.g. Skempton (1944, 1954, 1957), Karlsson and Viberg (1967), Wroth and Wood (1978), Stroud (1974), Wroth (1979), Carrier and Beckman (1984), Larsson et al. (1987), Nakase et al. (1988), Wood (1990), Tripathy and Mishra (2011), Sorensen and Okkels (2013) and Farias and Llano-Serna (2016)). The liquidity index (I_L) parameter is used in codified design approaches for deep foundations in Russia (see Vardanega et al. (2012), Vardanega and Haigh

(2014a) and Kolodiy et al. (2015)) and in geomorphological research to characterise soils at a more regional level (e.g., Amir-Faryar et al. (2015) and Stanchi et al. (2015)).

The coincidence of Atterberg limit values obtained using different testing methods has been a subject of considerable discussion. This paper begins by defining the various consistency limit parameters, their measurement methods and associated problems. The significance of differences in operator performance and judgement in *PL* determinations from the rolling out of soil threads is assessed in terms of some established correlations with the consistency limits. Alternative methods for *PL* determination are reviewed, including various fall-cone approaches, but since these are strength-based they do not measure the onset of brittleness and hence cannot measure the true *PL*. The significance of plausible differences in the strain-rate dependency on the mobilised fall-cone strength for different test soils is demonstrated. Various correlations are established relating *LL* values deduced using the main measurement techniques and standards, such that discrepancies between the different liquid limit measures can be taken into account when these are substantial. The paper concludes with recommendations on the standardisation of international codes and the wider used of the fall-cone approach as appropriate for soft to medium stiff clays in establishing the variability of strength with changing water content and further index parameters.

Consistency limits

Figure 1 shows schematically the relative locations of various index parameters positioned on the scale of water content, with their indicative remoulded undrained strength ranges presented in Fig. 2. A logarithmic scale is used for undrained strength since the correlation between the increase in undrained strength with reducing water content for a given soil can be derived from a semi-logarithmic plot or, alternatively, from a bi-logarithmic plot (after Kodikara et al., 1986, 2006). Each of these parameters is defined and their relative merit discussed in the following sections.

Liquid limit

Notionally the liquid limit of a soil is the water content at which it transitions from liquid to plastic behaviour. As the soil never has zero shear strength, the *LL* is determined as the water content associated with an arbitrarily chosen (low) strength on a continuum of ever-weakening behaviour with increasing water content. The *LL* value is strongly dependent on the soil grading, composition and mineralogical properties, particularly those of the clay fraction, and also the quantity of interlayer water in the case of expanding clay minerals (Dolinar and Trauner, 2004; Trauner et al. 2005; Wood, 1990).

As the liquid limit is only precisely defined by the test used to measure it, rather than representing some sudden change in behaviour, the value obtained for liquid limit is highly dependent on the technique used to measure it. This is problematic owing to the lack of worldwide standardisation of liquid limit techniques and equipment. Two techniques, the Casagrande percussion cup and fall-cone (cone penetrometer) methods have been adopted as the standard measurement approaches, with the former favoured in the United States of America (ASTM, 2010; AASHTO, 2010) and the latter adopted as the preferred approach in the United Kingdom (BSI, 1990) and by Eurocode 7 (BSI, 2007).

Within each of these two methods further variation exists. Casagrande (1958) bemoaned the lack of standardisation in percussion-cup device bases in use at that time, two decades after the test was introduced, saying "Unfortunately, no effort was made to specify the [base] hardness by a standard hardness test". When the test was standardised, each country appears to have taken the approach of mandating the range of devices in use in their country at that time, leading to a wide variety of base hardness and resilience values being specified for the percussion cup device, with no standardisation between countries (Haigh 2016). While such devices are often distinguished as soft- and hard-base devices, considerable variability exists even within each of these categories.

The fall-cone test is essentially an assessment of soil strength, relying on the work of Hansbo (1957) who related the penetration depth (d) of a fall-cone of weight W to the soil's remoulded undrained strength via:

$$s_{\mathrm{u\ FC}} = \frac{KW}{d^2} \tag{1}$$

where K is the fall-cone factor.

The effect of cone angle on the K factor from Equation (1) (and by definition the computed undrained shear strength) has been studied by various researchers (e.g., Houlsby, 1982; Wood 1985; Brown and Huxley, 1996).

The fall-cone *LL* test suffers from less variability in equipment and execution than the Casagrande cup test, in most localities utilising a standard 30°–80g cone penetrating 20 mm at liquid limit (i.e. LL_{FC}), this corresponding to a shear strength of approximately 1.7 kPa. Other cone angles and masses have been used, such as the 'Swedish cone' (i.e. 60°–60g cone penetrating 10 mm at LL_{FC} (e.g., Karlsson (1961)), which was also advocated by Koumoto and Houlsby (2001). Other 'non-standard' cones have been reported; e.g. a 30°–148g cone was used in the study of Sivapulliah and Sridharan (1985). As with the Casagrande cup apparatus, there are variations in the fall-cone *LL* approaches specified in different codes (involving cones of different masses and apex angles, with the index property values usually deduced for different cone penetration depths), and as such, the strength assumed for the fall-cone *LL* condition varies somewhat between different codes (cf. Budhu (1985), Leroueil and Le Bihan (1996) and Koumoto and Houlsby (2001)).

Plastic limit

The plastic limit of a soil is the water content at which it transitions from ductile to brittle behaviour. Unlike the liquid limit, this is a sudden definite change in behaviour that could in theory be measured with a variety of tests, each of which would be expected to give the same result. The international standard method for *PL* determination involves manually rolling out a thread of soil on a glass plate until it crumbles at a specified diameter (ASTM, 2010; BSI, 1990), possibly being caused by air-entry or cavitation within the soil thread (Haigh et al. 2013). It has been shown that the thread diameter requirement for the crumbling condition (specified as about 3.0 mm (BS 1377-2: BSI, 1990) or 3.2 mm (ASTM D4318–10e1: ASTM, 2010)) is not critical, with no statistically significant trend of varying water content with the soil thread diameter at failure (2–6 mm range investigated) reported for a variety of mineral (Prakash et al., 2009; Haigh et al., 2013, 2014) and organic (O'Kelly, 2015) soils.

REPEATABILITY OF THE THREAD ROLLING TEST

It has been argued that the values deduced by the thread-rolling method are overly dependent on operator performance and judgement (e.g., Sherwood (1970), Sherwood and Ryley (1970), Whyte (1982), Belviso et al. (1985) and Sivakumar et al. (2009)). To investigate this point, reported *PL*s determined independently by four site investigation laboratories for 11 inorganic fine-grained soils of intermediate to very high plasticity (see Table 1) were considered. The maximum difference in the measured *PL*s for a given soil type was 8%, although Sherwood

(1970) reported that the variation for engineering practice can be up to 12%. Using the data in Table 1, the significance of the maximum variation in the measured *PL*s for the different soils was assessed in the present study for four established and widely used correlations that make use of *PI* or I_L.

- *Insitu* undrained shear strength ($s_{\mathrm{u\,(insitu)}}$) as a function of plasticity index (*PI*) for normally consolidated soil given by Eq. 2 (e.g., Skempton (1954, 1957), which was later validated by an extended database in Wood (1990) — albeit with more scatter being shown than originally present in the work of Skempton).

$$\frac{s_{\mathrm{u\,(insitu)}}}{\sigma'_{vo}} = 0.11 + 0.37PI \qquad (2)$$

  where σ'_{vo} is the *insitu* vertical effective stress.

- Effective angle of shearing resistance as a function of logarithm *PI* for normally-consolidated reconstituted and undisturbed clays (Eq. 3, reported in Sorensen and Okkels (2013), based on a database of previously published data):

$$\phi'_{nc} = 43 - 10\log_{10}(PI) \qquad [R^2 = 0.41, n = 233] \qquad (3)$$

- The empirical factor (α_{FV}) used to obtain overconsolidation ratio (OCR) from normalised field vane strength ($s_{\mathrm{u\,FV}}/\sigma'_{\mathrm{vo}}$) data presented in Mayne and Mitchell (1988):

$$\alpha_{\mathrm{FV}} = \frac{OCR}{s_{\mathrm{u\,FV}}/\sigma'_{\mathrm{vo}}} = 22(PI)^{-0.48} \qquad [n = 263] \qquad (4)$$

- Remoulded undrained shear strength as a function of liquidity index (Eq. 5, after Wroth and Wood (1978)).

$$s_{\mathrm{u}}\ [\mathrm{kPa}] = 170\exp(-4.6\,I_{\mathrm{L}}) \qquad (5)$$

Based on the data in Table 1; for Eqs. 2–4 which make use of *PI*, the percentage variation in $s_{\mathrm{u\,(insitu)}}/\sigma'_{\mathrm{vo}}$ from its mean value would range between 2.2% and 10.7% considering all 11 soils, with respective values of 0.33% and 1.72% for ϕ'_{nc} and 1.1% and 5.2% for α_{FV}. In all cases considered, the minimum and maximum variations from the mean occurred for the Donegal Clay and Kaolin material, respectively, with these examples demonstrating that depending on the correlation and soil type considered, the potential variation can be significant (e.g., in the case of the $s_{u\,(insitu)}/\sigma'_{vo}$ value for the Kaolin), but in many correlations may not be. However, other correlations that make use of liquidity index (and activity) to evaluate other soil characteristics are likely to be influenced to a more significant degree. For instance, differentiating Eq. 5 gives

$$\delta s_u / s_u = -4.6 \delta I_L \tag{6}$$

so that an error of, for instance, 0.1 in I_L would give rise to an error of 46% in the estimate of s_u.

ALTERNATIVE APPROACHES FOR *PL* DETERMINATION

Mechanical thread-rolling

Attempts to improve on the standard *PL* test include the thread rolling methods proposed by Gay and Kaiser (1973) and Bobrowski and Griekspoor (1992), a mechanically adapted version of the Bobrowski and Griekspoor's device (Temyingyong et al., 2002), and Barnes (2009, 2013a, 2013b). The Barnes' apparatus can measure indicative stress and toughness values for the soil thread during the rolling out procedure, with control of the strain rate, but the added complexity introduced into the test does not substantially alter the results obtained for *PL*. Apart from the Bobrowski and Griekspoor (1992) approach, (a thread rolling device that comprised two flat plates covered with paper), which was subsequently adopted as a *PL* rolling device in ASTM (2010) and AASHTO (2000), none of the other proposed rolling methods have, to date, been adopted more widely. Further, the *PL*s obtained using the Bobrowski and Griekspoor device have been shown to generally underestimate the standard (thread rolling) *PL*s (Bobrowski and Griekspoor, 1992; Rashid et al., 2008; Ishaque et al., 2010), most likely because the paper tends to lead to inhomogeneity of the soil thread, the outside becoming drier than its centre, during the rolling out procedure.

Strength-based approaches

Many researchers have attempted to devise various strength-based approaches to the measurement of plastic limit. These are, in general, based on the assumption of a 100-fold gain in strength between the liquid and plastic limits, as proposed by Wroth and Wood (1978). As evident from Fig. 3, the strength gain factor (R_{MW}) for the traditionally defined plastic range is often significantly less than the assumed one-hundredfold increase. Prakash (2005) and Nagaraj et al (2012) also cautioned against assigning a fixed strength value at plastic limit. As explained in Haigh et al. (2013), the assumption of a 100-fold factor increase derives from the following passage in Schofield and Wroth (1968), who were examining the data of Skempton and Northey (1952) (shown on Figure 4):

> "experimental results with four different clays give similar variation of strength with liquidity index . . . From these data it appears that the liquid limit and plastic limit do correspond approximately to fixed strengths which are in the proposed ratio of 1:100."

Houston and Mitchell (1969) also recognised that variability of undrained strength at *PL* was present (their bounds are shown also on Figure 4). However, (as reviewed in Vardanega and Haigh, 2014b) the data of Skempton and Northey (1952) show variations in the strength gain factor (R_{MW}) value, which ranged between 70 and 160 for the four soils considered. Karlsson (1977) reported R_{MW} = 50–100 for some Swedish clays and Whyte (1982) suggested $R_{\mathrm{MW}} \approx 70$. Vardanega and Haigh (2014b) demonstrated using a database of 101 soils that the ratio of computed strengths from plastic limit to liquid limit was on average to be closer to 34.3 (when fall-cone strength, $s_{\mathrm{u\,FC}}$, was fitted to I_L) and 83.5 (when $s_{\mathrm{u\,FC}}$ was fitted to logarithmic liquidity index). Simply based on analysis of historical data, as the ratio of strengths at the plastic and liquid limits varies substantially between soils, these strength-based approaches can only coincidentally give true *PL* values, actually measuring what might be termed the plastic strength limit (PL_{100}); i.e. the water content corresponding to $s_{\mathrm{u\,FC}} = 100 \times s_{\mathrm{u\,FC}(LL)}$.

Fall cone (Wood and Wroth, 1978; Belviso et al., 1985; Wasti, 1987; Harison, 1988; Feng, 2000, 2001, 2004; Koumoto and Houlsby, 2001; Sharma and Bora, 2003; Lee and Freeman, 2009; Shimobe, 2010; Sivakumar et al., 2015), steady monotonic penetration (Stone and Phan, 1995; Stone and Kyambadde, 2007), fast-static loading (Sivakumar et al., 2009) and extrusion (Timár, 1974; Whyte, 1982; Medhat and Whyte, 1986; Kayabali and Tufenkci, 2010a, 2010b; Kayabali, 2011a, 2011b, 2012; Kayabali et al., 2016) approaches for *PL* determination have all been suggested as alternatives to the conventional thread-rolling approach. As mechanical tests, these strength-based approaches are seen by some researchers as means of achieving higher degrees of repeatability and reproducibility of results, although, to date, most fall-cone research has been conducted on well-behaved clay-rich soils that lie above the A-line on the standard plasticity chart (ASTM, 2011; BSI, 2015). While these tests do not measure the onset of brittleness and hence cannot measure the true plastic limit, they may in many cases be measuring a more useful parameter. If what is wanted is an indication of the variability of strength with changing water content, a strength test seems much more appropriate than a test of the onset of brittleness.

Other proposed approaches

Some researchers have attempted to devise relationships between the *PL* and other soil parameter measurements, including suction data (Uppal, 1966; McBride, 1989; McBride and Bober, 1989), effective stresses from consolidation tests (Youssef et al., 1965; Nuyens and Kockaerts, 1967; McBride and Bober, 1989; McBride and Baumgartner, 1992) and soil moisture tension (Livneh et al., 1970; Gadallah, 1973). However, since there is no unique value of suction, effective stress or undrained shear strength at the plastic limit for all soils, this invalidates these techniques for *PL* determinations.

As the plastic limit occurs at the onset of brittleness, methods of measurement based on the onset of cracking should in theory have a better chance of giving similar results. Attempts to do this include the cube method (Abdun-Nur, 1960) and indentation (de Oliveira Modesto and Bernardin, 2008) and thread bending (Moreno-Maroto and Alonso-Azcárate, 2015) tests; the latter based on the measurement of bending deformations. For the indentation test proposed by de Oliveira Modesto and Bernardin (2008), the force applied to a 30^{o} cone was slowly and steadily increased in order to indent the soil test-specimen, which was considered to be in a plastic state if the perforation mark printed on it presented no cracks. In other words, the deformation response indicates whether the soil is in a brittle (crack formation) or plastic state, rather than the magnitude of the applied force or indentation hardness. This approach can be contrasted with cone penetration methods in which a specified indentation depth for a particular load (i.e. the soil strength) is taken as the measurement of the plastic strength limit (e.g. Stone and Phan (1995)). Andrade et al. (2011) present a review of some other approaches for determination of soil plasticity, such as the 'Pferfferkorn', 'Penetration', 'Capillary Rheometer' and 'Torque Rheometer' methods.

Other factors influencing deduced Atterberg limit values

Other factors including the soil fraction tested, sample preparation technique adopted (i.e. testing of fine soil in its natural condition or of the homogenous soil paste produced using wet (preferred) or dry sample preparation techniques) and the chemistry and pH of any water added to the soil sample in preparing the soil paste for testing (Jang and Santamarina, 2016) can also influence the deduced values of liquid limit and plastic limit. For instance, the *LL* and *PL* values measured for peats and other organics soils are invariably strongly dependent on these factors (Hanrahan et al., 1967; Hobbs, 1986; Yang and Dykes, 2006; Asadi et al., 2011; O'Kelly, 2015). In the case of fibrous peat material, preloading (which gives the organic solids some stress history because of their compressible nature) produces lower *LL* values. Greater mechanical breakdown of the peat solids during sample preparation produces lower *LL*, *PL* and *PI* values, especially for less humified material (O'Kelly, 2015), such that measured plastic ranges were notional and unlikely to meaningfully correlate with mechanical (strength) behaviour (Hobbs, 1986; O'Kelly, 2015, 2016a; O'Kelly and Zhang, 2013). Further, the pH of water affects the cation exchange capacity of fine soil, such that even usage of distilled water in changing the consistency of the material for laboratory testing can lead to different remoulded shear strength and hence different *LL* than what might happen for the field material (Torrance and Pirnat, 1984). Sridharan (1991, 2014) gives a detailed review of the effects of varying exchangeable sodium on the liquid limit of kaolinitic and montmorillonitic soils.

PL_{100}: A new parameter for soil mechanics practice?

Having recognised the important distinction between the true plastic limit and that measured by strength based tests, the '*PL*' determined by the fall-cone approach has been referred to as the *plastic strength limit* (Haigh et al., 2013) PL_{100} (Harison, 1988; Stone and Kyambadde, 2007; Stone and Phan, 1995; Kyambadde and Stone, 2012; Haigh et al., 2013; O'Kelly, 2013; Kyambadde et al., 2014; Sivakumar et al., 2015), with the subscript 100 indicating that the defined strength is 100 times the strength mobilised for the fall-cone *LL* ($s_{\mathrm{u\,FC}(LL)}$). This assumes that cones having identical apex angle and surface roughness values are used in identifying both LL_{FC} and $PL_{100}$and, furthermore, that the strain-rate dependency of the soil remains the same (as considered in the next section).

Vardanega and Haigh (2014b) demonstrated from analysis of a large database of fall-cone test results that, for any given soil, acceptable linear correlations could be drawn between both the logarithm of strength and liquidity index and the logarithm of strength and a logarithmic liquidity index. While the ratios of strengths at the plastic and liquid limits varied between soils, defining any two (or more) points on these linear relationships would give good predictions of strengths at intermediate water contents. The measurement of PL_{100} together with the LL_{FC} would achieve this. By adopting a strength gain factor of 100 for the plastic range in defining the PL_{100}, however, more often than not, one would end up testing soils in their brittle state (i.e. $w < PL$) for water contents around PL_{100}. This has implications for the preparation of the test-specimens for fall-cone testing near the PL_{100} (Wood and Wroth, 1978; Whyte, 1982; Wasti and Bezirci, 1986; Harison, 1988; Stone and Phan, 1995; Feng, 2000), in that for many cases sample preparation is difficult and some test-specimens are likely not to be saturated, and calls into question the use of Hansbo's Eq. 1 for non-ductile materials. For $PL_{100} < PL$, the strain-rate dependence and deformation mode of the soil test-specimen will be significantly different for water contents between the PL_{100} and the PL (i.e. brittle state), as compared with $w > PL$, which brings into question the validity of any data extrapolation techniques for the scenario described.

An alternative and prudent approach, therefore, is to employ a lower R_{MW} value (<< 100) in defining the water content corresponding to the chosen fall-cone upper strength value (i.e. giving $PL_x > PL$). For instance, Koumoto and Houlsby (2001) suggested using $R_{MW} = 10$ (i.e. $s_{u\,FC}$ of 17 kPa), although this would result in a narrow strength range of 1.7–17 kPa in considering correlations between water content and $s_{u\,FC}$ values. By adopting a higher strength gain factor ($R_{MW} > 10$), the likelihood of the test soil occurring in a brittle state for water contents about the associated upper $s_{u\,FC}$ value will progressively increase (refer to Fig. 3). These tend to be conflicting requirements; on the one hand seeking to encompass a wide enough range of undrained strengths, but also requiring that the test soil is in a plastic state for water contents about the chosen upper $s_{u\,FC}$ value. On the basis of the ratios of strengths at the plastic and liquid limits reported in Haigh et al. (2013), the water content corresponding to 25 times the strength mobilised at LL_{FC} (defined as PL_{25}; i.e. $s_{u\,FC}$ = 42.5 kPa) would approximate the lowest expected strength value at the PL and also allow a good prediction to be made of the strength variation between LL and PL. For the standard 30°–80g fall cone, the proposed PL_{25} corresponds to a 4-mm penetration depth.

STRAIN RATE EFFECTS

For the fall-cone test, the strain rate changes continuously as the cone accelerates under gravity from a stationary position, penetrating the test-specimen and then decelerates before coming to rest, with the strain rate also dependent on the cone characteristics and penetration depth. For instance, typical mean strain rate ($\dot{\gamma}$) values of ~ 1.0×10^6%/h (0.89×10^6–1.15×10^6%/h for d = 15–25 mm) and 2.5×10^6%/h (1.94×10^6–3.37×10^6%/h for d = 15–25 mm) were reported for the 30°–80g and 60°–60g cones, respectively (Koumoto and Houlsby, 2001). For fall-cones incorporating a falling distance before the cone tip contacts the surface of the test-specimen (e.g. Sivakumar et al. (2015)), the strain rate would be greater.

The undrained strength of soil increases by approximately 10% per tenfold increase in strain rate (Ladd and Foott, 1974; Kulhawy and Mayne, 1990; Koumoto and Houlsby, 2001) (i.e. μ = 0.1, where μ is the rate dependence parameter). It is, however, not uncommon for the rate of strength increase to range between 5% and 15% (Ladd and Foott, 1974), with values of up to 30% measured for high organic content soils (O'Kelly, 2014, 2016b). Hence, for soil material having a greater rate dependence of strength, the average undrained strength value mobilised over the course of the cone penetration would be lower than that deduced from analysis of the fall-cone data using Eq. 1, and *vice versa*.

To demonstrate the effect of plausible differences in strain rate dependence on the mobilised fall-cone strength for different mineral soils, it can be deduced from Eq. 7 and Fig. 5 that, compared with the commonly assumed μ value of 0.10, the K value for the same smooth 30° cone could potentially vary by –16.9% (μ = 0.15) to +25.4% (μ = 0.05). In other words, putting aside uncertainty regarding the cone roughness (adhesion factor), the static strength mobilised for the 30° fall cone can vary by up to ±20.3% from the value computed using Eq. 1, depending on the soil's level of strain-rate dependence in the probable range of μ = 0.05–0.15.

$$K = \frac{3\zeta}{\pi\, N_{ch}\, \tan^2(\beta/2)} \qquad \text{(Koumoto and Houlsby, 2001)} \qquad (7)$$

where β is the cone apex angle, N_{ch} is a dimensionless bearing-capacity factor that takes into account the heave of the soil surface resulting from the cone's penetration and ζ is the ratio of the 'static' ($s_{\mathrm{u\,FC}}$) to fall-cone dynamic ($s_{\mathrm{u_d}}$)strength values.

For the 30°–80g fall-cone test (BS EN 1377–2: BSI, 1990) and assuming a semi-rough cone (i.e. with adhesion factor (α) value of 0.5 => N_{ch} = 7.952, after Hazell (2008)), this would imply an $s_{u\,FC}$ range of 1.6–2.4 kPa for the LL_{FC} condition, as defined by d = 20 mm. Note, using Hansbo's K values of 0.80 and 0.27 for the 30° (80 g) and 60° (60 g) cones, respectively, Farrell et al. (1997) computed $s_{u\,FC(LL)}$ of 1.57 and 1.59 kPa, respectively; consistent with the lower end of the identified LL strength range. Assuming the μ value of a given test soil remains unchanged with reducing water content and providing the test soil remains in a plastic condition; on this basis, the $s_{u\,FC}$ value mobilised for a heavier 30°–8kg fall cone at d = 20 mm (i.e. at PL_{100}) could range between 160 and 240 kPa. Note that with R_{MW} = 100 and $s_{u\,FC(LL)}$ = 1.7 kPa, the $s_{u\,FC}$ value of 170 kPa is near the lower end of the identified PL_{100} strength range.

Heretofore, it has generally been taken that the LL_{FC} corresponds to a fixed strength value; e.g. from theory, $s_{u\,FC}$ = 2.66 kPa for the 30°–80g at LL_{FC}, after Koumoto and Houlsby (2001), although this strength value seems rather high, with the Casagrande LL value normally taken, *on average*, as 1.7 kPa (Wroth and Wood, 1978). However, the above example demonstrates that even for a given cone setup, the $s_{u\,FC(LL)}$ value mobilised can vary relatively significantly and will also vary between setups having different cone characteristics and penetration depths used in defining the LL_{FC}.

For pile design, studies of glacial soils and submarine soil investigations for offshore structures, etc., the design engineer is interested in the remoulded undrained strength, but as demonstrated earlier, the soil's level of strain rate dependence in the plausible range of μ = 0.05–0.15 has a significant influence on the mobilised $s_{u\,FC}$ value. From this point of view, displacement-controlled fall cone devices (e.g., the soil mini-penetrometer for quasi-static undrained strength determinations described by Stone and Kyambadde (2007)) offer a more reliable approach in determining undrained strength and PL_{100} values since adjustments for strain-rate effects are not necessary.

GEOTECHNICAL CORRELATIONS

It has been demonstrated that the precise liquid and plastic limit values obtained for any given soil depend substantially on the techniques used to measure them. The values of liquid and plastic limit obtained are used both in order to classify soil and to determine other soil parameters through correlation. It is the outcome of these processes which is more important to design than the precise values of liquid and plastic limit obtained.

The standard plasticity chart (ASTM, 2011; BSI, 2015) was developed from that proposed by Casagrande (1947) based on *LL* and *PL* values deduced using the ASTM Standard percussion-cup and thread rolling methods. Hence, from a purist's viewpoint, only the Casagrande *LL* (LL_{cup}) and thread-rolling *PL* (but not LL_{FC} (Prakash and Sridharan, 2006; Prakash et al., 2009)) values should be used for soil classification purposes using the standard plasticity chart or in the multitude of correlations with directly useful design parameters built up over the decades using LL_{cup} and standard *PL* data. As in many countries the LL_{cup} is no longer measured, it is useful to investigate the correlation between LL_{FC} and LL_{cup} values such that account can be taken of discrepancies between the different liquid limit measures when these are substantial.

Comparison of the fall-cone LL and Casagrande LL

Liquid limits obtained using the Casagrande cup and fall-cone apparatus share a similar approach, despite the difference in measurement technique. The Casagrande cup (Haigh, 2012) and the fall-cone (Kuomoto and Houlsby, 2001) measure the shear strength of the soil and this is associated with *LL*. The Casagrande cup device imposes shock loading to the soil test-specimen as the cup repeatedly impacts against the apparatus base, initiating a slope failure. This scenario has been shown to measure a certain specific strength (i.e. strength divided by soil density) value at LL_{cup} of approximately 1 m^2/s^2 (Haigh, 2012). The LL_{FC} on the other hand corresponds to a fixed reference strength value, independent of soil density. This difference accounts for the systematic bias between these two approaches with higher values being obtained for the Casagrande cup device compared to the fall cone for high liquid limit materials. A semi-logarithmic relationship of decreasing shear strength for the LL_{cup} with increasing values of liquid limit was identified by Youssef et al. (1965). Haigh (2012) demonstrated that using an appropriate correction for this factor gave good agreement between LL_{cup} and LL_{FC} results, without the necessity of invoking different strength regimes for high *PI* and low *PI* soils, as has been suggested by Sridharan et al (1999) and Sridharan and Prakash (2000).

Many studies have reported on the relationship between LL_{cup} (Casagrande 1932, 1958) and LL_{FC} (e.g., Karlsson, 1961; Škopek and Ter-Stepanian, 1975; Littleton and Farmilo, 1977; Garneau and LeBihan, 1977; Moon and White, 1985; Queiroz de Carvalho, 1986; Wasti and Bezirci, 1986; Wasti, 1987; Christaras, 1991; Koester 1992; Mohajerani, 1999; Prakash and Sridharan, 2006; Deka et al., 2009; Claveau-Mallet et al., 2012), with the divergence of these measurements well noted for w > ~ 120% (Škopek and Ter-Stepanian, 1975; Wasti, 1987; Leroueil and Le Bihan, 1996; Farrell et al., 1997; Mohajerani, 1999; Feng, 2001; O'Kelly, 2013).

For soil having a low liquid limt (< 50% (Budhu, 1985); < 60% (Prakash and Sridharan, 2006)), the LL_{cup} deduced for the hard base cup and the LL_{FC} deduced for the 30º–80g fall-cone produce broadly comparable results (Wasti and Bezirci, 1986), since this fall-cone setup was benchmarked to produce essentially the same results as the Casagrande cup device. For the low to medium *LL* soils commonly used in engineering works, LL_{cup} is generally slightly lower than LL_{FC}, as demonstrated by Belviso et al. (1985), Wasti and Bezirci (1986) and Di Matteo (2012), to name a few. For instance, Di Matteo (2012) reported that for fluvial-lacustrine soils from Central Italy, LL_{FC} was about 2.2–2.8 points higher than LL_{cup}. Hence, with *PL* obtained from thread-rolling, a general small increase in *PI* occurs for low to medium liquid limit soil when LL_{FC} is used in the calcualtion. While this small change in the measured liquid limit valuewith a change in method does not represent a change in material behaviour, in some instances it is sufficient to change the classification of a soil from suitable to unsuitable (or *vice versa*) owing to precise thresholds of allowable *LL* and (or) *PI* values. For instance, Di Matteo et al. (2016) reported specific problems that arose when LL_{FC} was adopted over LL_{cup} in *PI* calculations for assessments of the suitability of deposits for two earthworks projects in Italy. It was found that for 18% of the soil samples investigated, the classification position according to the standard plasticity chart changed, moving them toward groups with poorer geotechnical qualities, resulting in contradictory and wrong classification compared with that deduced for LL_{cup}.

Inconsistencies may also arise for fall-cone *LL* testing of fine soils having high silt and (or) sand contents, which plot below the A-line on the standard plasticity chart, and also for high and very high plasticity soils (Prakash and Sridharan, 2006; Poulsen et al., 2012). These inconsistencies should be taken into account when changing the standard method of testing, with classification boundaries being moved to respect the inherent relationship between the liquid limit values obtained using the two different approaches.

Correlating fall-cone LL with Casagrande LL

In order to achieve the desired corrections to soil classification procedures, correlations are required between results obtained from the two approaches for *LL* determinations. In this section, using a large database (see Table 2) assembled from the literature, correlations are established relating LL_{FC} with LL_{cup} determined for different standards. For each dataset considered, LL_{cup} results determined for the British and ASTM Standards' soft- and hard-base percussion cups, respectively, were reported along with the corresponding British Standard (BS) (30°–80g cone) LL_{FC} test results. The available data allowed separate regression analyses considering: (i) LL_{FC} versus BS 'soft base'cup ($LL_{\mathrm{BS\ cup}}$) (Figures 6 and 7); (ii) LL_{FC} versus ASTM 'hard base'cup ($LL_{\mathrm{ASTM\ cup}}$) (Figures 8 and 9). The following regression curves were obtained from Figures 6 to 9:

$$LL_{\mathrm{FC}} = 1.86 \times LL_{\mathrm{BS\ cup}}^{0.84} \qquad [R^2 = 0.98,\ n = 216] \quad \text{full range of } LL \qquad (8)$$

$$LL_{\mathrm{FC}} = 1.62 \times LL_{\mathrm{BS\ cup}}^{0.88} \qquad [R^2 = 0.96,\ n = 199] \quad \text{for } LL_{\mathrm{BS\ cup}} < 120\% \qquad (9)$$

$$LL_{\mathrm{FC}} = 1.90 \times LL_{\mathrm{ASTM\ cup}}^{0.85} \qquad [R^2 = 0.97,\ n = 199] \quad \text{full range of } LL \qquad (10)$$

$$LL_{\mathrm{FC}} = 1.45 \times LL_{\mathrm{ASTM\ cup}}^{0.92} \qquad [R^2 = 0.97,\ n = 188] \quad \text{for } LL_{\mathrm{ASTM\ cup}} < 120\% \qquad (11)$$

Eqs. 8 to 11 are shown plotted on Fig. 10. Compared to the hard Micarta base of the ASTM cup device, the softer rubber base of the BS cup device consistently gives higher liquid limit values since more energy is absorbed by it during the repeated impacts of the cup holding the soil test specimen (Norman, 1958; Whyte, 1982; Sridharan and Prakash, 2000; Haigh, 2016). For this reason, Haigh (2016) cautioned against direct comparisons of LL_{cup} results from the soft- and hard-base Casagrande cup approaches due to differences in base hardness.

Consistent with the findings of Belviso et al. (1985), Wasti and Bezirci (1986), Prakash and Sridharan (2006) and Di Matteo (2012); from Eqs. 8–11, the BS LL_{FC} is slightly greater than both the $LL_{\mathrm{BS\ cup}}$ and $LL_{\mathrm{ASTM\ cup}}$ for low and intermediate *LL* soil. Strong divergence between LL_{cup} and LL_{FC} is also evident for the combination of BS LL_{FC} with both $LL_{\mathrm{BS\ cup}}$ and $LL_{\mathrm{ASTM\ cup}}$, as evident in Figs. 6, 8 and 10 (supporting the findings of Škopek and Ter-Stepanian, 1975; Wasti, 1987; Leroueil and Le Bihan, 1996; Farrell et al., 1997; Mohajerani, 1999; Feng, 2001).

RECOMMENDATIONS FOR THE FUTURE

Methods for measuring LL

Despite the long history of the Casagrande cup apparatus and the enormous amount of data derived from it used in correlations, the lack of consistency between different apparatus (even when nominally they corresponding to the same standard) makes it non-ideal for such a widely used test. Even if the will were present to do so, the complexity of ensuring that base hardness was standard between devices at manufacture and remained so through their working life would be difficult with such a wide variety of devices in current usage. A standardised fall-cone device is a more appropriate methodology for measuring liquid limit in such a way as to get the same result, independent of where and when the test is undertaken.

An internationally standardised fall-cone *LL* setup should specify the cone mass, apex angle, surface roughness and penetration depth at the *LL*. Although the 60^{o} cone is less sensitive to variations in cone roughness (Koumoto and Houlsby, 2001) and, as a result, can arguably produce greater repeatability between geotechnical laboratories, the 30^{o} cone is in much wider use and from this consideration would be the more obvious choice for international standardisation. However, an internationally standardised fall-cone *LL* setup will not overcome variations in mobilised $s_{\mathrm{u\,FC}(LL)}$ arising from differences in the strain rate dependency of strength between different soils.

Proposed method for measuring PL_{25} **and** *PL_{100}*

At present, no substantially better method of measuring the onset of brittleness has been developed than Atterberg's thread-rolling method. If a standard fall-cone setup is to be used for the liquid limit test, however, it would be of value to consistently report a further parameter, termed the PL_{25}; i.e. the water content corresponding to $25 \times s_{\mathrm{u\,FC}(LL)}$ at which the strength is approximately 42.5 kPa. For the standard 30°–80g fall cone, the proposed PL_{25} corresponds to a 4-mm penetration depth. Note, the strengths corresponding to the LL_{FC} and PL_{25} are termed the fall-cone lower strength parameter and fall-cone upper strength parameter ($s_{\mathrm{u\,FC}(PL_{25})}$), respectively. This approach would allow better correlations to be achieved between strength and a new fall-cone consistency index (I_{FC}; Eq. 12) for soft to medium stiff clays than can be achieved with a conventional liquidity index based on the onset of brittleness at $I_L = 0$.

$$I_{FC} = \frac{\log LL_{FC} - \log w}{\log LL_{\mathrm{FC}} - \log PL_{25}} \tag{12}$$

with I_{FC} being defined in logarithmic form since the bi-logarithmic undrained strength–water content correlation provides a regression coefficient value closer to unity compared with the semi-logarithmic form when considering a wide water content (plastic range) for a given soil.

In the proposed framework, the fall-cone strength ($s_{\mathrm{u\,FC}}$) value corresponding to any water content value within the plastic range ($w < PL$) can then be approximated as:

$$\log s_{\mathrm{u\,FC}} \approx I_{FC} \log\left(s_{\mathrm{u\,FC}(PL_{25})} / s_{\mathrm{u\,FC}(LL)}\right) + \log s_{\mathrm{u\,FC}(LL)} = I_{FC} \log(25) + \log s_{\mathrm{u\,FC}(LL)} \tag{13}$$

which simplifies to the following equation (i.e., assuming $s_{\mathrm{u\,FC}(LL)}$ = 1.7 kPa for $I_{FC} = 0$):

$$\log s_{\mathrm{u\,FC}} \approx 1.4 I_{FC} + 0.23 \tag{14}$$

Equation 14 gives an $s_{\mathrm{u\,FC}}$ value of 42.5 kPa for $I_{FC} = 1$ (i.e. at PL_{25}), with the approximation sign in this equation reflecting probable differences in the mobilised $s_{\mathrm{u\,FC}}$ value on account of the different rate dependence of different soils. In a similar way, these equations can be used to estimate the $s_{\mathrm{u\,FC}}$ values corresponding to PL_{100} (i.e. $I_{FC} = \log 100 / \log 25 = 1.43$) and more generally PL_x, including the corresponding water content values. Further, if the standard PL has also been measured using the thread-rolling method, the corresponding $s_{\mathrm{u\,FC}}$ value and hence R_{MW} value can be estimated using the same approach.

Consistency of reporting using appropriate terminology

Liquid and plastic limit values are often reported in the literature without reference made to the methods and (or) standards used for their determination, which introduces additional uncertainty in using these data correctly for soil classification purposes or in correlations. Hence, it is important that appropriate terminology, including references to the test methodologies employed in deducing these index values, are reported (e.g. the fall-cone *LL* test performed to the British Standard gives the British Standard LL_{FC} value (BS EN 1377–2: BSI, 1990)), both for the test results and when reporting allowable ranges in design codes of, for instance, liquid limit or in correlations with other soil parameters.

SUMMARY

The variation of techniques and equipment used to measure liquid limit can result in substantial variations in the measured values for a given soil. The fall-cone *LL* device is a more appropriate methodology, with the 30°–80g fall cone recommended as the international standard. As demonstrated in the paper, the mobilised liquid-limit strength will still vary slightly between different soils, depending on their strain-rate dependence of strength.

While Atterberg's thread-rolling method may appear unscientific, it is currently the most appropriate technique to use if the water content for the brittle–ductile state transition is required. The strength-based approach employed with the fall-cone methods cannot be used to determine Atterberg's *PL*. Further, since the strength gain over the plastic range is, *on average*, significantly less than 100, the PL_{100} water content is frequently less than Atterberg's *PL* water content; i.e. the soil would be tested while in a brittle state for water contents near the PL_{100}.

To overcome difficulties (e.g. specimen preparation, the need for significant extrapolation on cone penetration depth against water content plots and significantly different strain-rate dependence expected for the brittle and plastic soil), the authors recommend PL_{25} (to replace PL_{100}) as the fall-cone upper strength parameter, which can readily determined along with the LL_{FC} parameter value using the standard 30°–80g fall cone. From these two measurements, a methodology has been presented for the determination of the undrained strength corresponding to any water content within the plastic range for soft to medium stiff clays, allowing substantially better strength predictions than existing correlations based on liquidity index.

NOTATION

The following symbols are used in this paper:

d	= cone penetration depth;
K	= cone factor;
I_{FC}	= fall-cone consistency index;
I_L	= liquidity index;
LL	= liquid limit;
$LL_{ASTM\ cup}$	= Casagrande liquid-limit derived from ASTM ‘hard-base’cup;
$LL_{BS\ cup}$	= Casagrande liquid-limit derived from BS ‘soft-base’cup;
LL_{cup}	= Casagrande liquid-limit water content;
LL_{FC}	= fall cone liquid-limit water content;
N_{ch}	= dimensionless bearing-capacity factor;
n	= number of data points used to generate a regression;
OCR	= overconsolidation ratio;
PI	= plasticity index (= $LL - PL$);
PL	= Atterberg’s plastic-limit water content;
PL_x	= water content corresponding to x times $s_{u\,FC(LL)}$;
PL_{25}	= water content corresponding to fall-cone upper strength parameter;
PL_{100}	= water content corresponding to $s_{u\,FC}$ = 100 × $s_{u\,FC(LL)}$;
R_{MW}	= strength gain factor;
W	= weight of fall cone;
$s_{u\,(insitu)}$	= *insitu* undrained shear strength;
s_u	= saturated remoulded undrained strength;
$s_{u\,FC}$	= fall-cone strength;
$s_{u\,FC(LL)}$	= fall-cone strength at liquid limit (i.e. fall-cone lower strength parameter);
$s_{u\,FC(PL_{25})}$	= fall-cone upper strength parameter (i.e. 25 × $s_{u\,FC(LL)}$);
$s_{u\,FV}/\sigma'_{vo}$	= normalised field vane strength;
s_{u_d}	= dynamic undrained strength mobilised in fall-cone test;
$s_{u\,(LL)}$	= undrained strength at liquid limit;
R^2	= coefficient of determination;

w	= water content;
α	= cone adhesion factor;
α_{FV}	= ratio of *OCR* to normalized field vane strength;
β	= cone apex angle;
ζ	= ratio of $s_{\mathrm{u\,FC}}$ to $s_{\mathrm{u_d}}$;
ϕ'_{nc}	= effective angle of shearing resistance of normally consolidated material;
σ'_{vo}	= *insitu* vertical effective stress;
$\dot{\gamma}$	= strain rate;
μ	= rate dependence parameter.

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TABLE CAPTIONS

Table 1. Liquid limits and plastic limits of soils obtained through different laboratories operating in Northern Ireland to BS EN 1377 (BSI, 1990). GSI: Glover Site Investigation Ltd; CPD: Central Procumbent Division, NI; WF: Whiteford Geoservices; QUB: Queen's University Belfast. (table adapted from Sivakumar et al. 2015) © ICE Publishing

Table 2. Sources of data in the database

FIGURE CAPTIONS

Figure 1: Schematic diagram for various index parameters

Figure 2. Undrained strength ranges for various index parameters plotted on logarithmic strength scale. Note, † deduced in the present investigation

Figure 3: Cumulative distribution of shear strengths of soil at plastic limit (Plot from Haigh et al. 2013) © ICE Publishing

Figure 4: Variation of remoulded undrained strength with liquidity index (data from Skempton and Northey (1952) and Houston and Mitchell (1969)) [Plot from Haigh et al. 2013] © ICE Publishing

Figure 5: Plot of ζ against the rate dependence parameter (μ), determined from numerical analysis of the fall-cone test (smooth 30º cone) (data from Hazell, 2008, pp. 136).

Figure 6: British Standard fall cone limit versus British Standard Casagrande cup liquid limit (BS1377: BSI, 1975, 1990) (data of *LL* < 600%)

Figure 7: British Standard fall cone limit versus British Standard Casagrande cup liquid limit (BS1377: BSI, 1975, 1990) (data of *LL* < 120%)

Figure 8: British Standard fall cone limit versus ASTM Casagrande cup liquid limit (data of *LL* < 600%)

Figure 9: British Standard fall cone limit versus ASTM Casagrande cup liquid limit (data of *LL* < 120%)

Figure 10: Comparison of fitting equations

Figure01

Click here to download Figure Figure01.tif

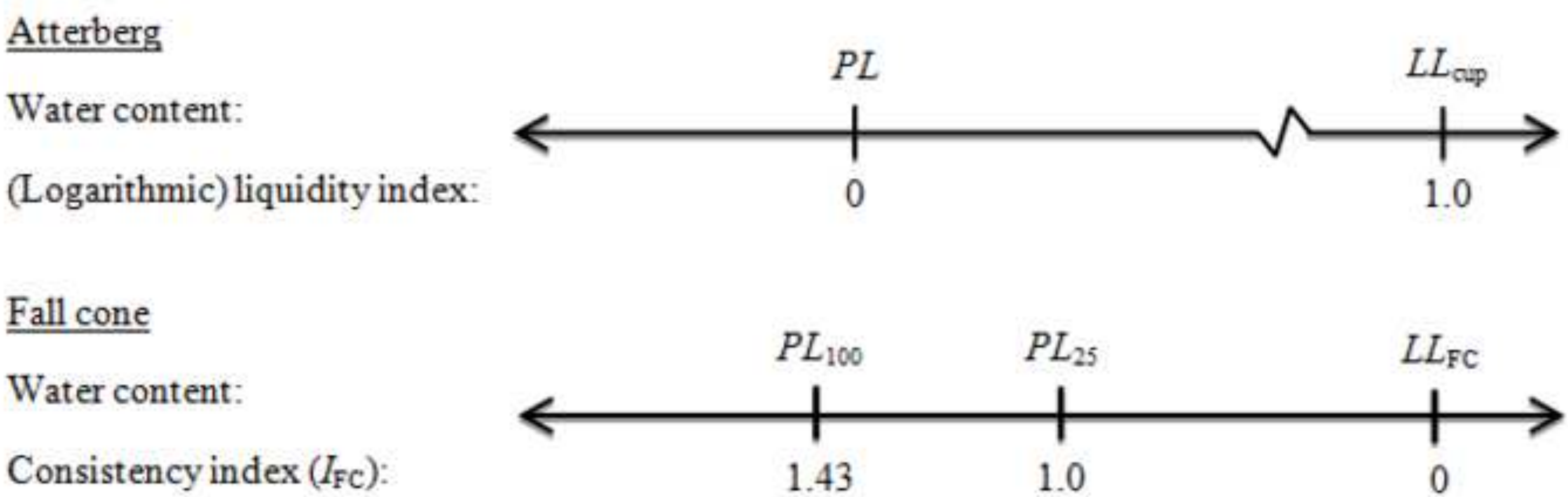


Figure02

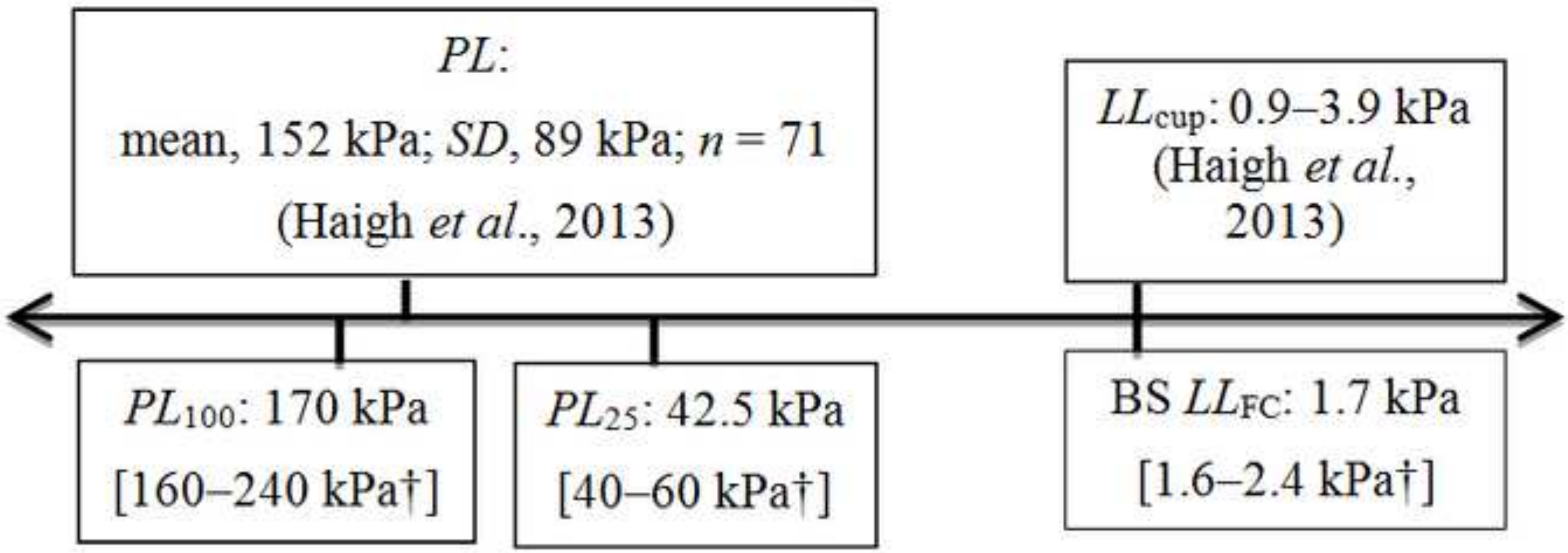
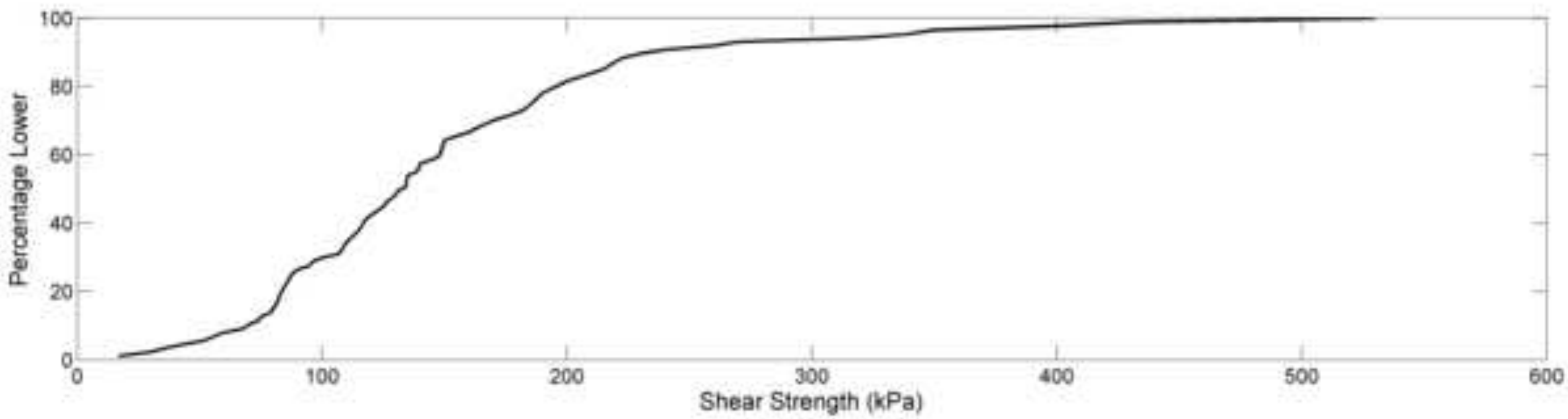
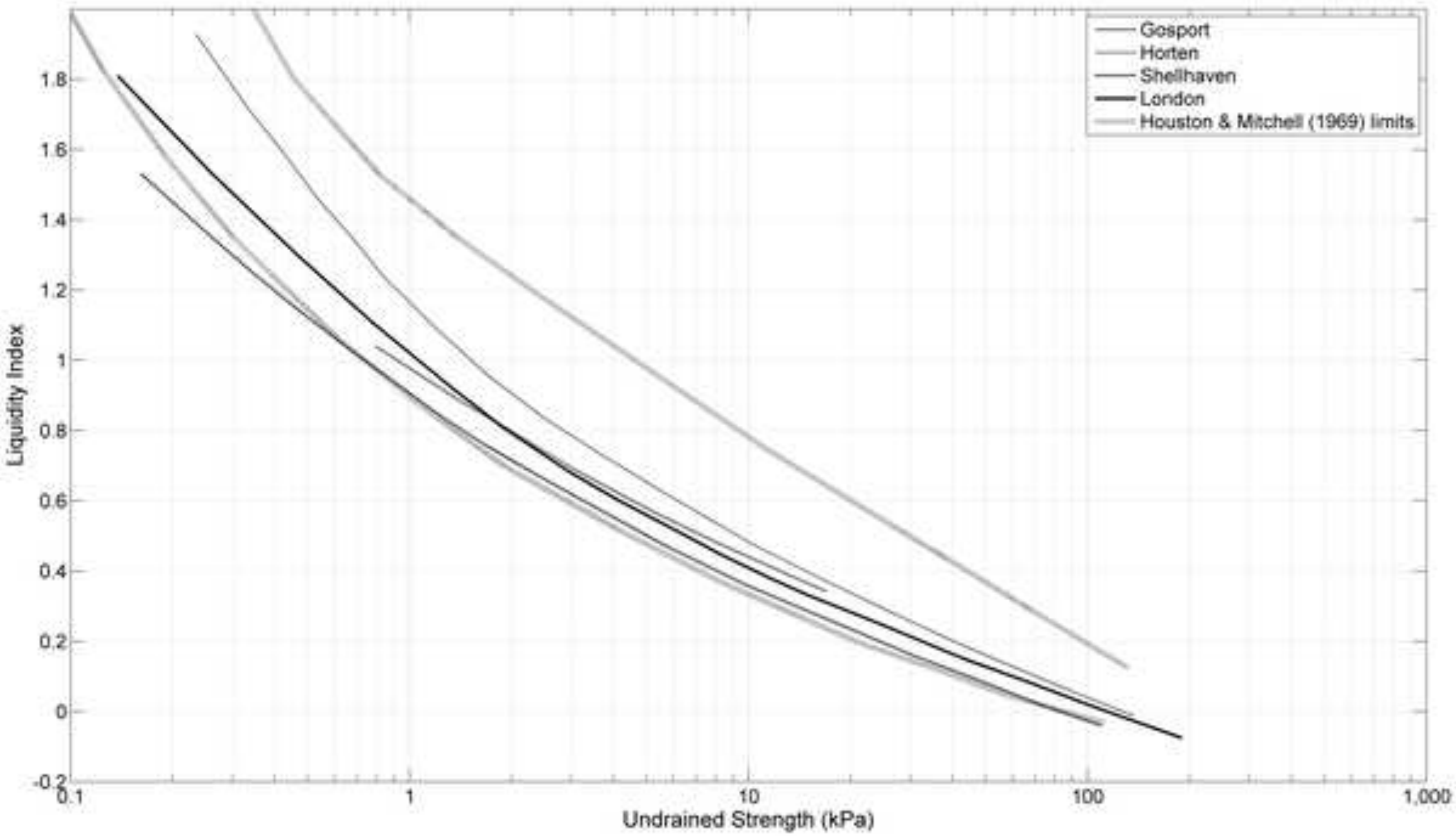

PL:
mean, 152 kPa; SD, 89 kPa; n = 71
(Haigh et al., 2013)
LLcup: 0.9–3.9 kPa
(Haigh et al., 2013)
PL100: 170 kPa
[160–240 kPa†]
PL25: 42.5 kPa
[40–60 kPa†]
BS LLFC: 1.7 kPa
[1.6–2.4 kPa†]

Figure03

Click here to download Figure Figure03.tiff

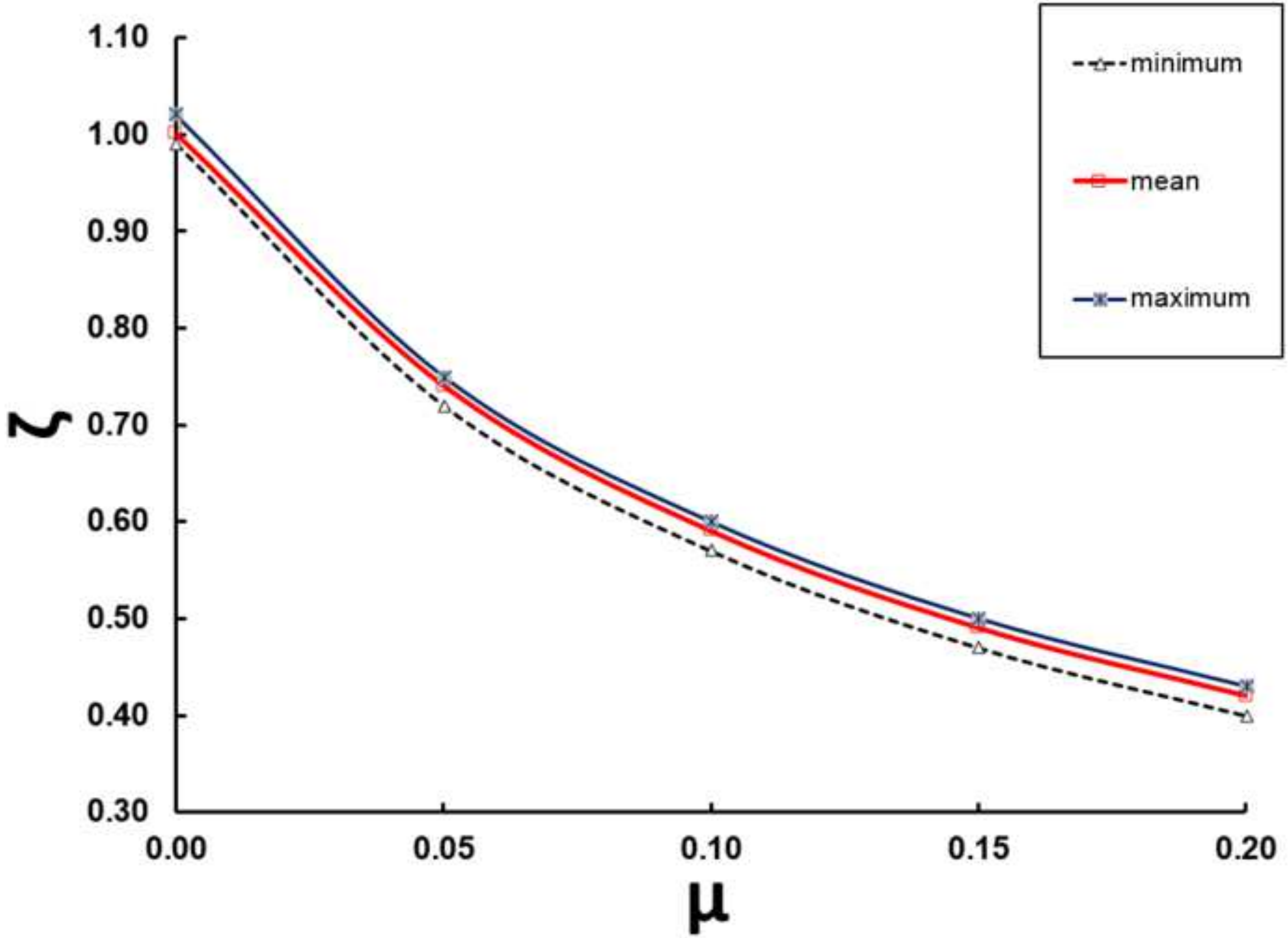


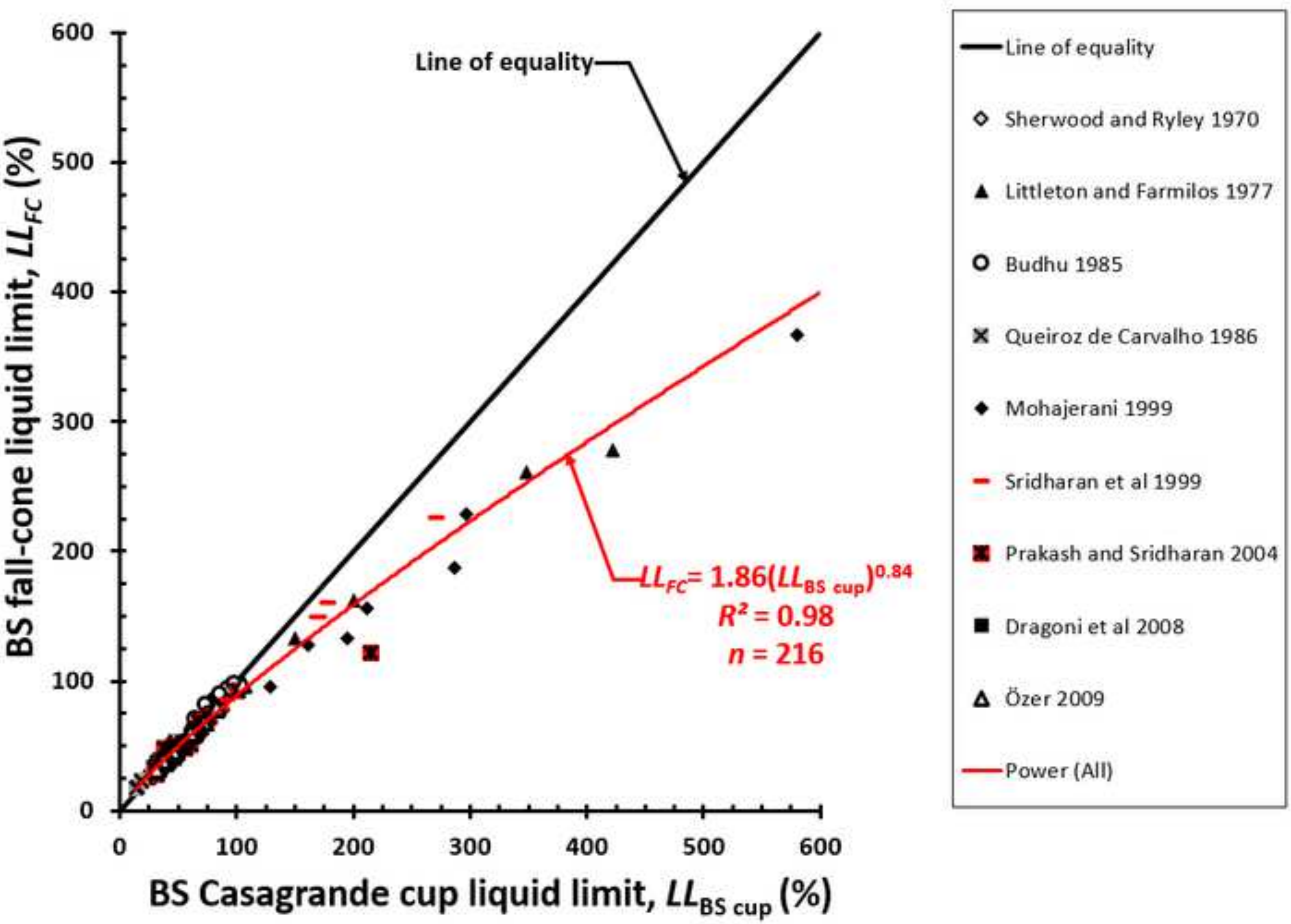


Gosport
Horten
Shellhaven
London
Houston & Mitchell (1969) limits
Liquidity Index
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0.1
1
10
100
1,000
Undrained Strength (kPa)

Figure05

Click here to download Figure Figure05.tif





Line of equality
Sherwood and Ryley 1970
Littleton and Farmilos 1977
Budhu 1985
Queiroz de Carvalho 1986
Mohajerani 1999
Sridharan et al 1999
Prakash and Sridharan 2004
Dragoni et al 2008
Özer 2009
Power (All)
$LL_{FC} = 1.86(LL_{BS\ cup})^{0.84}$
$R^2 = 0.98$
$n = 216$
BS fall-cone liquid limit, LL_{FC} (%)
BS Casagrande cup liquid limit, $LL_{BS\ cup}$ (%)
0
100
200
300
400
500
600

Figure07

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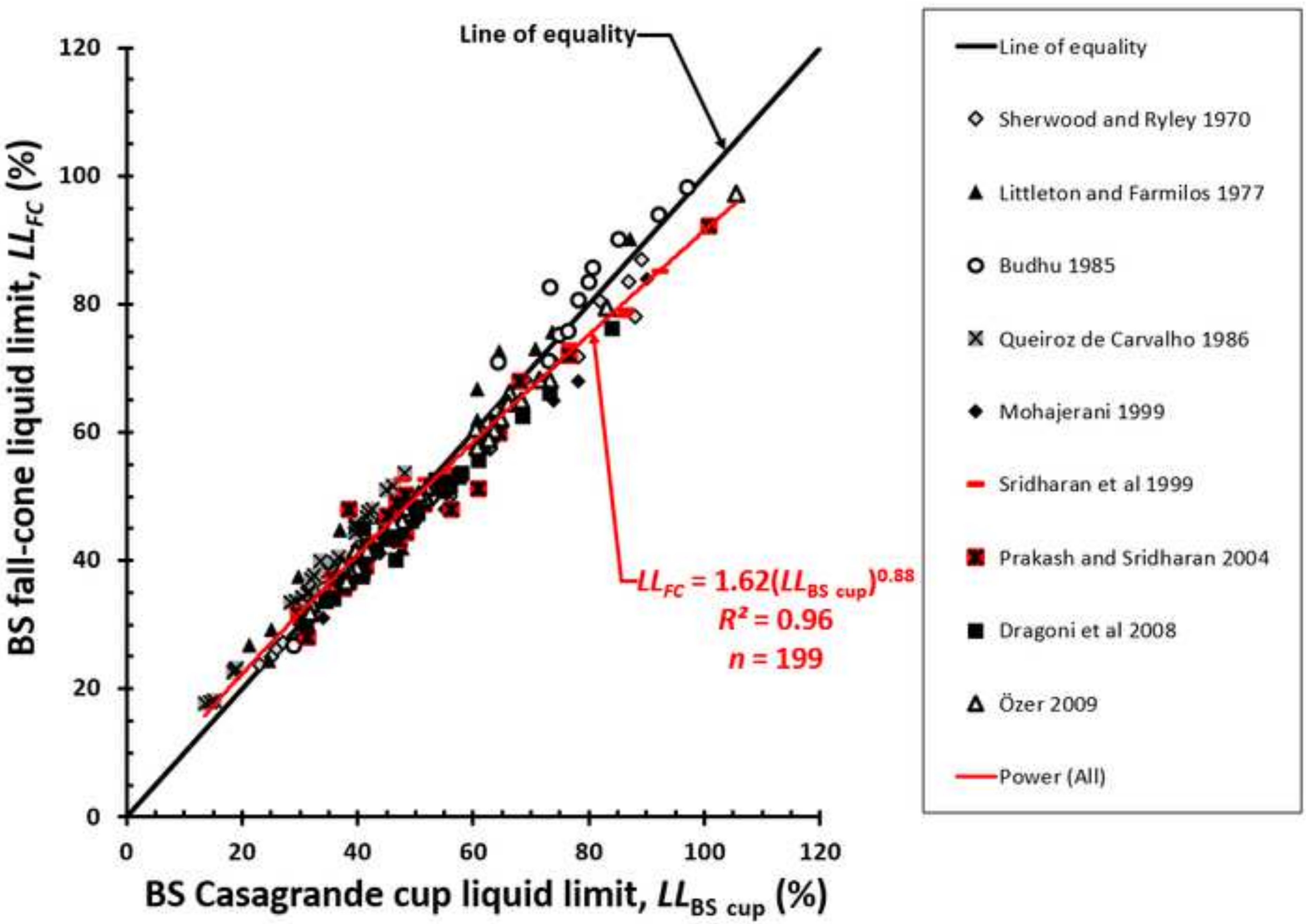

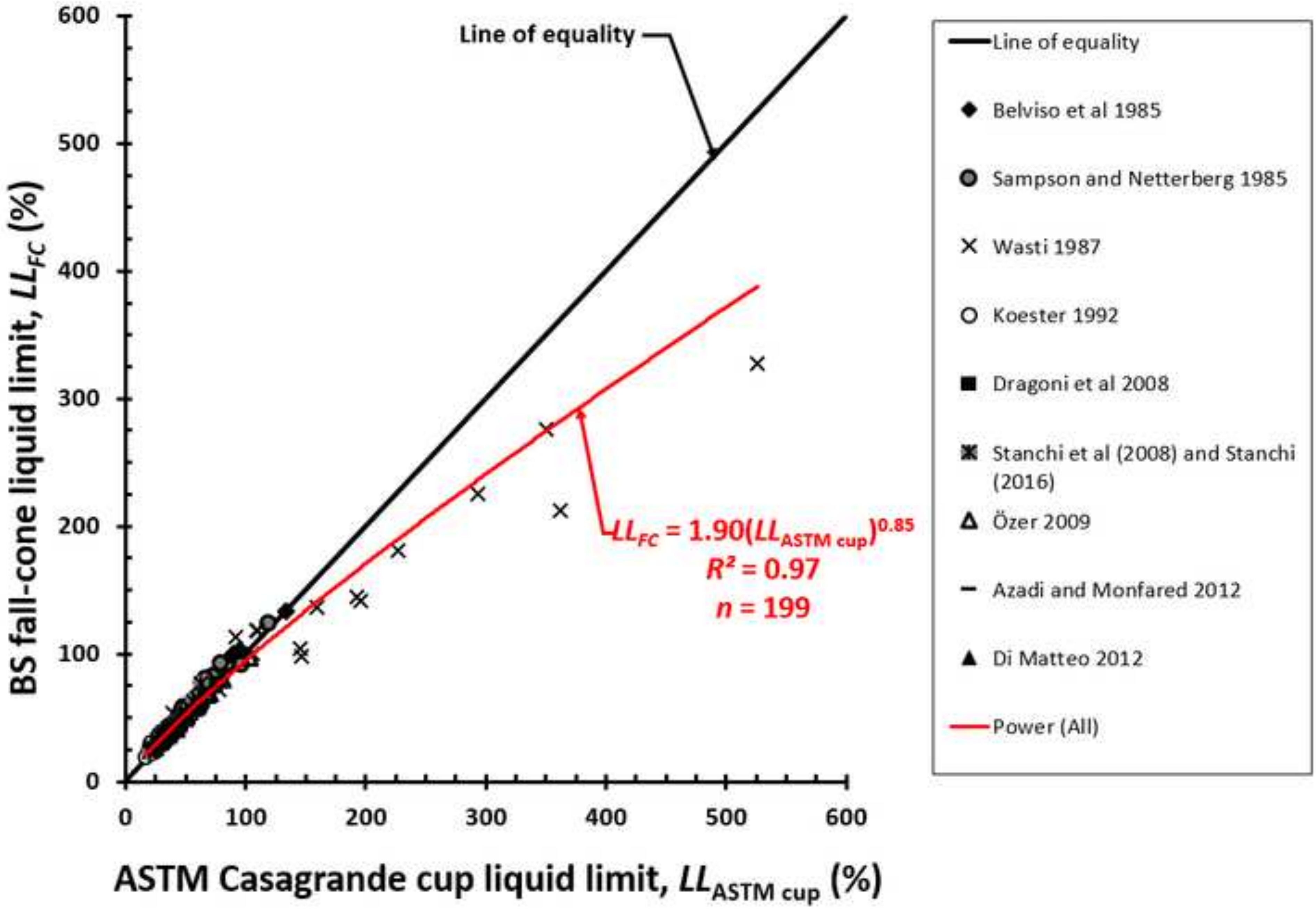
Line of equality
Belviso et al 1985
Sampson and Netterberg 1985
Wasti 1987
Koester 1992
Dragoni et al 2008
Stanchi et al (2008) and Stanchi (2016)
Özer 2009
Azadi and Monfared 2012
Di Matteo 2012
Power (All)
$LL_{FC} = 1.90(LL_{ASTM\ cup})^{0.85}$
$R^2 = 0.97$
$n = 199$
BS fall-cone liquid limit, LL_{FC} (%)
ASTM Casagrande cup liquid limit, $LL_{ASTM\ cup}$ (%)
0
100
200
300
400
500
600

Figure09

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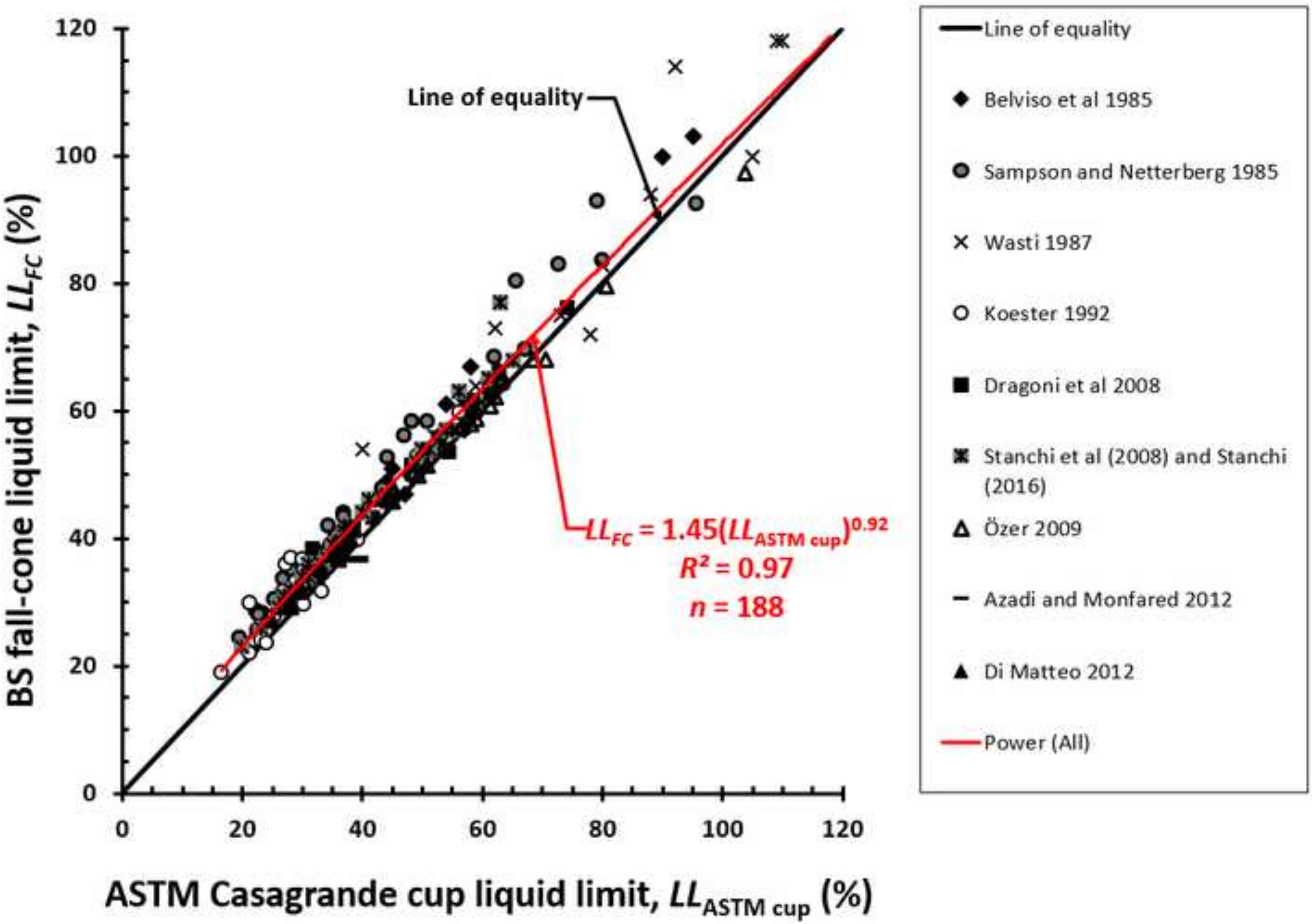

Figure10

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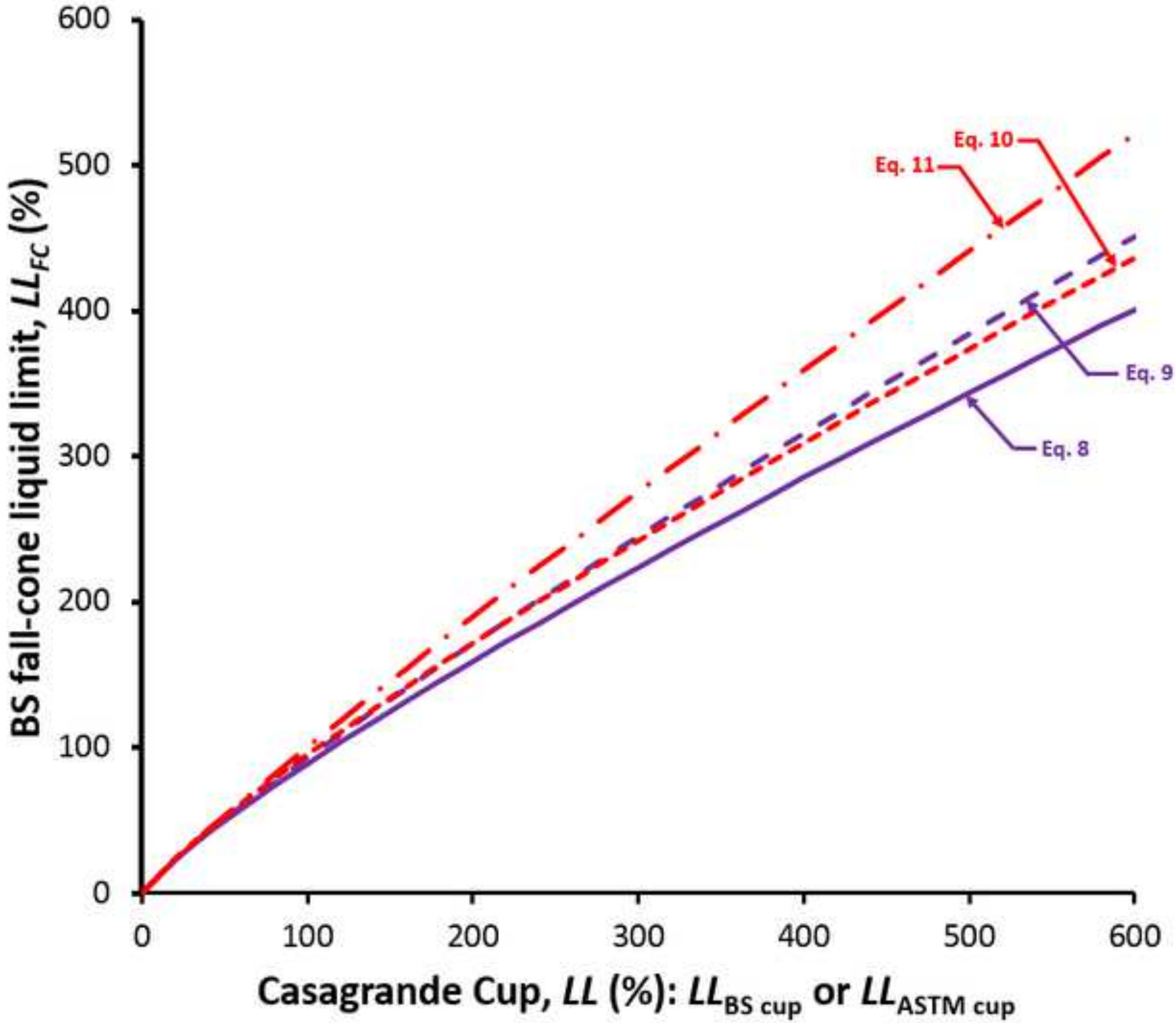

Table 1. Liquid limits and plastic limits of soils obtained through different laboratories operating in Northern Ireland to BS EN 1377 (BSI, 1990). GSI: Glover Site Investigation Ltd; CPD: Central Procumbent Division, NI; WF: Whiteford Geoservices; QUB: Queen's University Belfast. (table adapted from Sivakumar et al. 2015) © ICE Publishing

Type of Soil	LL_{FC} (%)	Thread rolling *PL* (%)				Average *PL* (%)	Maximum difference (%)
		GSI	CPD	WF	QUB		
Sleech	50	25	25	24	23	24.3	2
Belfast Clay	55	24	26	26	23	24.8	3
Oxford Clay	55	24	22	23	20	22.3	4
Canadian Clay	73	27	30	30	27	28.5	3
Glacial till	36	17	17	16	14	16.0	3
Tennessee	72	28	33	35	30	31.5	7
Ampthill	77	31	32	33	30	31.5	3
Donegal Clay	43	21	20	20	20	20.3	1
London Clay	71	28	21	30	27	28	3
Enniskillin	36	18	19	17	16	17.5	3
Kaolin	70	33	36	37	29	33.8	8

Table 2. Sources of data in the database

Reference	Fall cone used	Percussion cup used	No. soil tests	Notes
Sherwood and Ryley (1970)	BS (30°–80g)	BS	25	Interpretation of LL_{FC} also given in Vardanega and Haigh (2014b)
Littleton and Farmilo (1977)	BS (BS1377-1975)	BS (assumed)	19	Data digitised from original figure (2)
Budhu (1985)	BS (BS1377-1975)	BS	17	
Belviso et al. (1985)	BS (BS1377-1975)	ASTM (ASTM D423-66)	16	
Sampson and Netterberg (1985)	BS (BS1377-1975)	ASTM style cup (South African method)	43	
Queiroz de Carvalho (1986)	BS (BS1377-1975)	BS (BS1377-1975)	27	
Wasti (1987)	BS (BS1377-1975)	ASTM	25	Data also in Wasti and Bezirci (1986)
Koester (1992)	Similar to BS (30°–76g cone, d = 17 mm) – quoted as PRC cone	ASTM style cup (US Army Corps cup)	26	Digitised from the original source
Sridharan et al. (1999)	BS (BS1377-1990)	BS	19	
Mohajerani (1999)	BS (AS2189-1991)	BS (AS2189-1995) (2009 standard considered 'soft base' by Haigh (2016)	19	
Prakash and Sridharan (2004)	BS (BS1377-1990)	BS	28	
Dragoni et al. (2008)	BS (BS1377-1990)	BS and ASTM (ASTM D4318-05)	30	Not every soil was tested with the ASTM cup
Stanchi et al. (2008) and Stanchi (2016)	BS (BS1377-1990)	ASTM (ASTM D4318-00)	34	
Özer (2009)	BS (BS1377-1990)	BS and ASTM (ASTM D4318-05)	32	
Di Matteo (2012)	BS (BS1377-1990)	ASTM (ASTM D4318-00)	6	
Azadi and Monfared (2012)	BS	ASTM	2	