Citation: O'Kelly, B.C. (2022) Appraisal of novel power-based extrusion methodology for consistency limits determinations of fine-grained soils. In: *Proceedings of the Civil Engineering Research in Ireland 2022 Conference*, 25–26 August 2022, Dublin, Ireland (Holmes, N., de Paor, C., and West, R.P. (Eds.)). Civil Engineering Research Association of Ireland. Vol. 1, pp. 317–322.

Appraisal of novel power-based extrusion methodology for consistency limits determinations of fine-grained soils

Brendan C. O'Kelly[1]
[1] Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin D02 PN40, Ireland
email: bokelly@tcd.ie

ABSTRACT: The consistency limits (liquid limit LL and plastic limit PL) are among the most commonly performed tests in geotechnical engineering practice, being used for classification of fine-grained soils and in deducing other parameters (e.g., shear strength, permeability, compressibility), necessary for preliminary design/assessments, via numerous correlations built up over the decades. Depending on geographic region and/or referenced standard, the LL testing is performed using either the fall-cone or Casagrande (percussion-cup) approaches, while Atterberg's PL is universally determined using the thread-rolling method. Because of its dependence on operator judgement regarding the crumbling condition during the rolling-out procedure, the accuracy of the PL test has been called into question by some researchers. This has prompted various alternative proposals, including undrained strength-based fall cone and extrusion approaches, but these are not appropriate for the determination of Atterberg's PL which defines the water content at the plastic–brittle transition point (i.e., not strength-based). This paper presents the culmination of a two-year research project performed at Trinity College Dublin on the investigation and development of a novel power-based extrusion methodology for determination of the consistency limits of fine-grained soils.

KEY WORDS: Atterberg limits; cohesive soil; extrusion; strength; workability.

1 INTRODUCTION

Plasticity of fine-grained soils is considered a function of the liquid limit (LL) and plastic limit (PL), these consistency limit parameters having wide importance for civil/geotechnical engineering and agronomic applications, and in the ceramic industry and brick manufacturing process. The LL, notionally understood as the water content below which fine-grained soil ceases to flow as a liquid, is invariably determined using the fall-cone or Casagrande (percussion-cup) approach. The PL (i.e., the water content at the plastic–brittle transition point) — originally proposed by Atterberg (1911) — identifies a genuine observable transition in soil behaviour, as conventionally determined by rolling-out on a glass plate of soil threads for the standard PL test. Various alternative experimental approaches have been proposed, particularly for PL determination, typically involving variants of the fall-cone approach, but also investigating the extrusion method (see the review papers by O'Kelly (2019, 2021b) and O'Kelly et al. (2018)). Proposed fall-cone approaches define a 'plastic strength limit' PSL (term coined by Haigh et al. (2013)) water content, typically associated with a remoulded undrained shear strength (s_{ur}) value of 100-fold greater than that mobilised at the fall-cone LL (i.e., LL_{FC}) water content. It must be emphasised that the PSL and Atterberg's PL are fundamentally different parameters (Haigh et al., 2013; O'Kelly, 2013; Sivakumar et al., 2016).

Extrusion involves the reduction in cross-sectional area of a billet (fine-grained soil test-specimen for the purposes of this investigation) by forcing it to flow through a die orifice under the action of an extrusion pressure. There are two approaches, direct extrusion and reverse extrusion (see Figure 1); the latter generally being preferred for soil mechanics' applications, since the friction component (mobilised between the test-specimen and the chamber side-wall) associated with direct extrusion does not arise for the reverse extrusion approach.

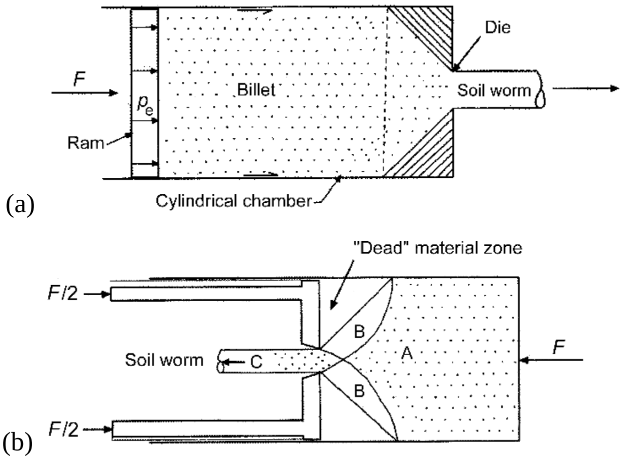


Figure 1. Schematic diagram of typical experimental set-up for (a) direct extrusion, and (b) reverse extrusion (after O'Kelly, 2019).

The first attempts at using the direct and reverse extrusion methods for consistency limits determinations of fine-grained soils were reported by Timár (1974) and Whyte (1982), respectively. Several testing parameters affect the extrusion force F_e (extrusion pressure p_e), such as the cylindrical chamber's geometry/dimensions and extrusion ratio R, the ram displacement rate (velocity), ram–chamber side-wall friction, and (for direct extrusion) the soil specimen–side-wall friction. Note: $p_e = F_e/A_o$ and $R = A_o/A_f$, where A_o is the bore cross-sectional area of the cylindrical chamber and A_f is the die orifice area. The principal material parameter affecting the extrusion force for testing of fine soil is its undrained shear strength (s_u) (which is dependent on the water content) (O'Kelly, 2019).

Recent research and findings suggest that the conventional extrusion approach, as presently applied, is not suitable (does not provide accurate/reliable experimental results) for consistency limits determinations or s_u measurement of fine-grained soils (O'Kelly, 2019, 2021a). Advocates of the soil extrusion approach argue that these shortcomings can be attributed to limitations of the conventional testing methods for consistency limits and s_u determinations. However, current uncertainties about the conventional extrusion approach for testing of fine-grained soils appear to be far greater (O'Kelly, 2019), including the question of the soil billet's assumed undrained condition, in that, depending on the soil mineralogy and gradation, localised billet consolidation could occur for the combination of slow extrusion (displacement) rates employed and high p_e values required, particularly for stiffer test soils (O'Kelly, 2019). Another important point is that compared to conventional s_u tests (e.g., direct shear (shearbox), undrained triaxial compression), the mechanics of the extrusion method are significantly different, with the process of soil extruding via the die orifice(s) resembling a material 'flow' test (O'Kelly, 2019) — the significant material parameter being the material flow stress. The test soil yields when it enters the shear zone (fan), and it is difficult to see how the material flow stress is not directly related to the s_{ur} parameter. However, based on a reassessment of extensive reverse-extrusion datasets for many hundreds of different fine-grained soils reported in the existing literature, O'Kelly (2019) found that for a given extrusion apparatus and die orifice combination, the p_e magnitudes corresponding to the Casagrande-cup LL, LL_{FC} and Atterberg PL states are not unique, rather the experimental p_e magnitude associated with each of these state parameters can vary over a wide range when considering different test soils, seemingly being dependent on the soil plasticity (plasticity index).

As described in Barnes' PhD dissertation (Barnes, 2013b), various context-specific definitions/criteria of workability exist in different disciplines. For instance, workability is of importance in the ceramics industry (e.g., for assessment of clays used in white-ware production), in the brick manufacturing industry, and in an agricultural context with respect to the efficiency of machinery in ploughing and tilling a clay soil. Workability is also a term associated with freshly made concrete — being assessed using the slump tests (i.e., the ease with which the fresh concrete flows, as evaluated from the stability of the concrete cone). In Soil Mechanics, toughness and workability are interchangeable terms used to explain the resistance to deformation of a soil, being applied to cohesive soils, and mainly clays (Barnes, 2013b; O'Kelly et al., 2022).

2 PROPOSAL OF POWER-BASED EXTRUSION TESTING APPROACH FOR CONSISTENCY LIMITS

Starting from mechanics definitions of work done (W = force × distance; that is, $F\,\Delta x$) and power ($P = W/\Delta t$, where Δt is the time period of soil deformation), it is proposed to investigate the concept of power, in the context of soil extrusion, when developing an alternative approach for consistency limit determinations of fine-grained soils. In other words, the methodology — originally proposed in the MSc research dissertation by Manafighorabaei (2017), and which was supervised by the Author — is that for a particular experimental setup (i.e., extrusion apparatus and die-orifice combination), specific values of power [J/s] could be required to cause extrusion of fine-grained soils to occur at their consistency limits. That is, the particular power values assigned for LL and PL (i.e., $P_{(LL)}$ and $P_{(PL)}$, being obtained from calibration of the extrusion apparatus) could be considered as corresponding to the 'workability' of fine-grained soils at these limit states.

The extrusion apparatus, as a soil deformation system, simply provides the experimental setup for quantification of the billet's resistance to deformation for a given water content w (or liquidity index, I_L) value, with $I_L = 0$ and 1 for PL and LL, respectively. So, in terms of the definition, power $P = F_e\,\bar{v} = p_e\,A_o\,\bar{v}$, with the average ram velocity $\bar{v} = \Delta x/\Delta t$; Δx being the ram displacement occurring for the extrusion period, Δt. For a given fine-grained soil, the magnitude of F_e increases with decreasing water content w (or I_L) of the soil billet (test specimen). The resistance offered is also dependent on the extrusion ratio, considering the number and combined area of the die orifices through which the soil billet is extruded.

For apparatus calibration, a series of extrusion tests are performed, ideally investigating a range of water contents about each of the conventionally determined LL and PL states. However, from various practicalities of performing the extrusion testing, the investigated water content range may be confined to within the plastic range, and often limited to $I_L = 0$ to 0.5 (e.g., Kayabali et al. (2015)). From the obtained P–w relationship, the power magnitudes associated with the consistency limit states are established, which may involve extrapolation using linear regression. Based on these calibrated power values, the hypothesis is that, based on the extrusion method, the consistency limit states of a general fine-grained soil could then be established, as follows. Analogous to the semi-logarithmic $s_{ur} - w$ (or I_L) relationship commonly adopted for strength interpolations, the water contents corresponding to the consistency limit states of the test soil could potentially be interpolated from its semi-logarithmic experimental P–w (or I_L) relationship. In the present paper, the 'power' hypothesis is first demonstrated using a purpose-build extrusion apparatus in testing the fine fraction of a Dublin Brown Boulder Clay sample. The veracity of the hypothesis and obtained results are then scrutinised in the context of the conventional consistency limit states (LL and Atterberg PL).

3 TCD EXTRUSION APPARATUS AND POWER-BASED TESTING APPROACH FOR CONSISTENCY LIMITS

This section presents an overview of the purpose-build extrusion apparatus developed in the Department of Civil, Structural and Environmental Engineering, Trinity College Dublin (TCD), over the period March 2015 to February 2017. Full details on the development, proposed testing method and calibration (from testing of 10 fine-grained soils) of the TCD extrusion apparatus are presented in the MSc research dissertation by Manafighorabaei (2017). The purpose of the prototype apparatus (overall 57-cm high × 16-cm square in plan dimensions, as shown in Figure 2) was to experimentally demonstrate the proposed methodology. The direct extrusion method was adopted for its simplicity [the reverse extrusion approach (which negates the soil specimen–side-wall friction effect) could be the subject of investigation in future studies].

Referring to Figure 2, the load (stress) controlled loading (due to the self-weight of the moving ram assembly) applies a constant vertical force F_e (extrusion pressure p_e), via the ram, to the soil billet (remoulded soil paste) contained in the cylindrical chamber, causing downwards extrusion (i.e., direct extrusion) of the soil to occur through the die orifices in the chamber base. A loading hanger and lever arrangement (acting on the ram assembly) may be used to apply greater extrusion force for specimens tested at higher s_{ur}. The vertical movement of the ram is guided by four linear bearings moving along vertical guide rods (see Figures 2 and 3).

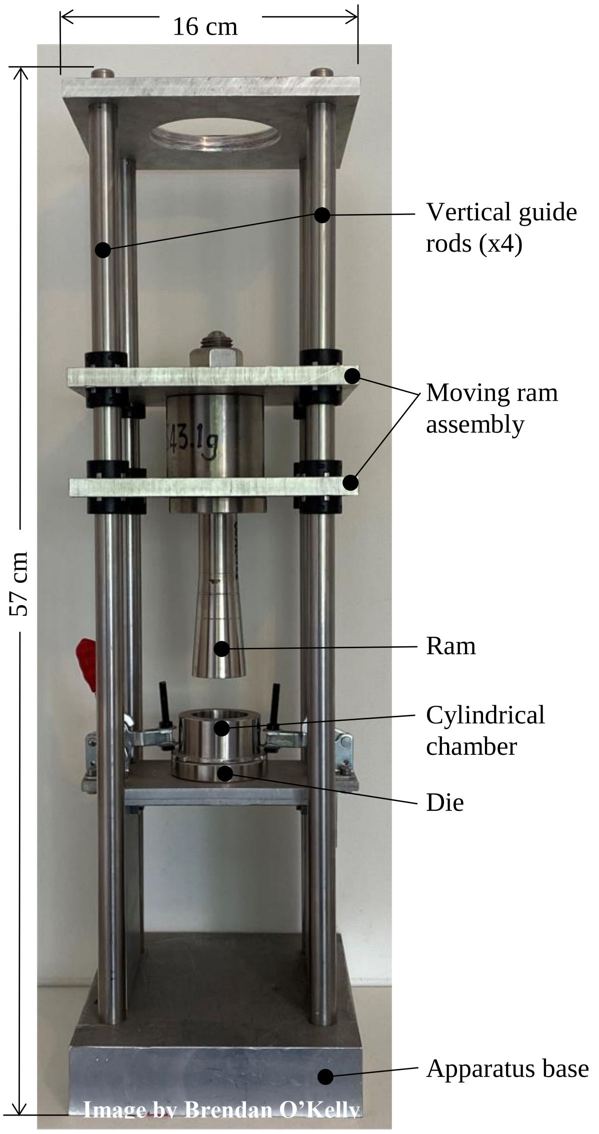
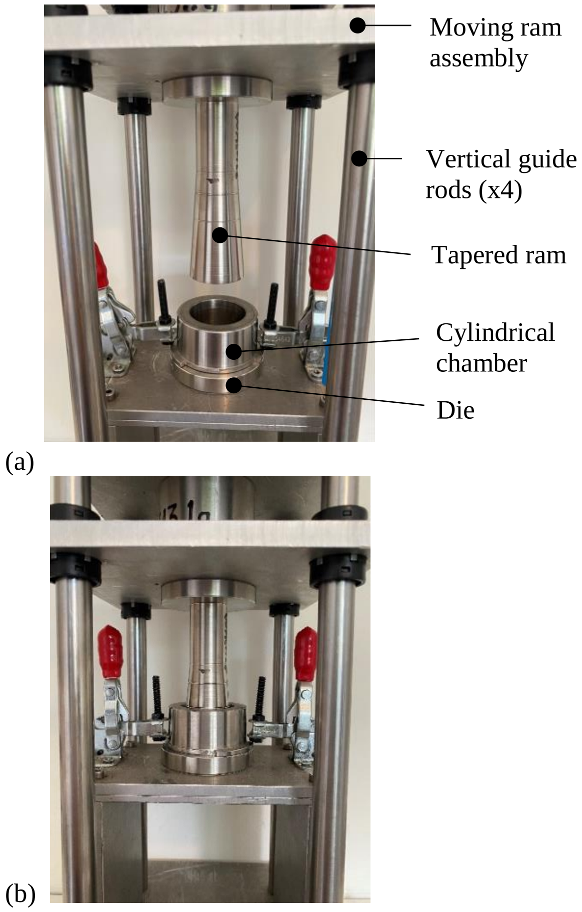


Figure 2. TCD direct-extrusion apparatus for testing fine-grained soils

Referring to Figure 4, the cylindrical chamber has inner diameter and depth dimensions of D = 35 mm and L = 50 mm, respectively; i.e., the short test-specimen length (reducing from 50 mm initially, to zero for full extrusion) means that the billet–side-wall friction effect could be considered negligible. Various die-orifice configurations (i.e., producing different R values) were trialled (full details are presented in Manafighorabaei (2017)) to arrive at suitable experimental set-ups, with consideration of the system's loading capacity and the soil consistency (s_{ur}) range tested when performing extrusion at various water contents, including about the consistency limit states. The configurations finally adopted for investigating the LL and PL states using the TCD extrusion apparatus were seven distributed die orifices, each of 5-mm and 10-mm in diameter, respectively (i.e., producing extrusion ratios of R = 7.0 and 1.75, respectively). Figure 4 shows the cylindrical chamber and die combination employed for LL testing.



(a)

(b)

Figure 3. Photographs of TCD extrusion apparatus showing: (a) ram located above cylindrical chamber; (b) ram at full penetration of chamber.

Figure 5 shows the placement of the chamber–die combination in the extrusion apparatus. A small clearance (gap) between the chamber's inner wall surface and penetrating ram prevents friction developing between them. The ram is also tapered (reducing in diameter along its length) for this purpose.

Based on testing of ten fine-grained soils, as reported in Manafighorabaei (2017), the calibration procedure for the TCD extrusion apparatus, with presented die orifice combinations, resulted in $P_{(LL)}$ = 0.171 J/s and $P_{(PL)}$ = 0.749 J/s being tentatively assigned for the LL_{FC} (i.e., 30°–80 g cone) and PL. Furthermore, extrusion pressures of $p_{e(LL)}$ = 35.6 kPa and $p_{e(PL)}$ = 495.4 kPa, as described in Manafighorabaei (2017), were tentatively assigned for the LL_{FC} and PL, respectively.

In performing the extrusion testing, the cylindrical chamber is completely filled with the remoulded fine-grained soil sample under investigation (i.e., initially L = 50 mm). The deformation work is given by the area under the experimental p_e vs. Δx curve, with the p_e magnitude (applied as maintained load F_e) remaining approximately constant throughout the extrusion test. In applying the proposed power-based extrusion approach for consistency limits determinations, taking LL_FC for demonstration purposes; with P = 0.171 J/s, $p_{\mathrm{e(LL)}}$ = 35.6 kPa, and A_o = 962 mm^2, the average ram velocity can be calculated as $\bar{v} = P/p_\mathrm{e}\ A_\mathrm{o}$ = 5.0 mm/s. Similarly, the average ram velocity for the PL would be calculated as $\bar{v}$ = 1.67 mm/s. It is emphasised that these values of P and $\bar{v}$ specifically relate to the TCD extrusion apparatus and die-orifice combinations employed in the present study (different configurations would require separate calibration and will have different P and $\bar{v}$ value combinations associated with the consistency limits). Note the methodology presented in Manafighorabaei (2017), and implemented in the present paper, has been modified to produce a larger and more complex soil-extrusion device (with pneumatic-actuator loading system) and 'workability' methodology, as presented in the paper by Manafi et al. (2022).

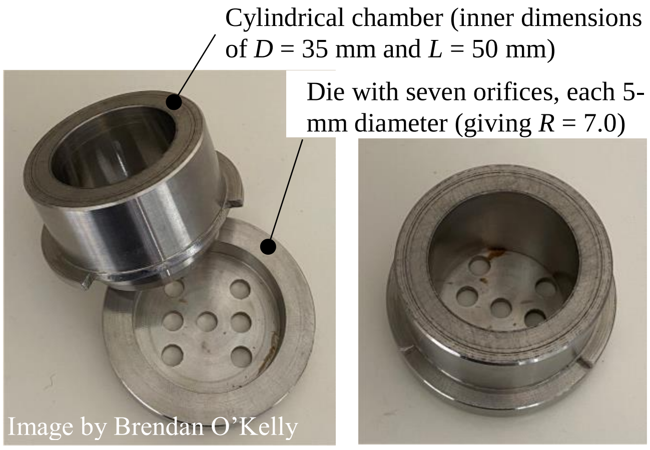


Figure 4. Chamber and die combination for LL testing in TCD extrusion apparatus: disassembled (left); assembled (right).

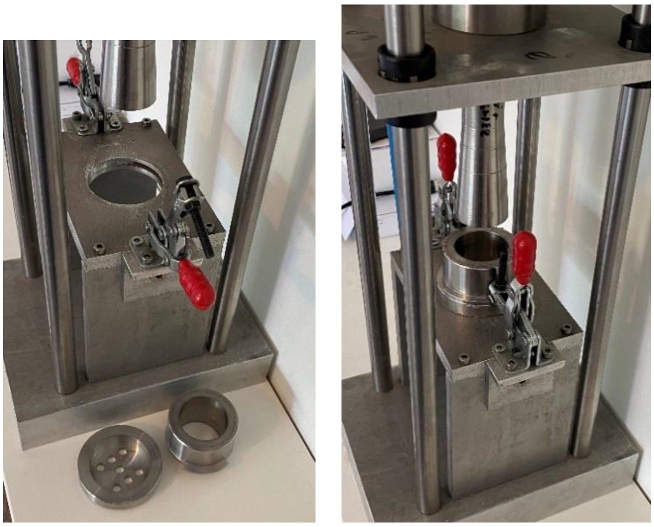


Figure 5. Placement of chamber and LL die combination in TCD extrusion apparatus: unassembled (left); assembled (right).

Hence, in essence, adopting a ram displacement of Δx = 50 mm (i.e., the ram penetrates to the full depth of the cylindrical chamber) for both consistency limits, the operator performs separate extrusion experiments for various (typically 4) water contents about the investigated consistency limit (LL or PL), with the associated extrusion time (Δt) for each water content measured using a stopwatch. Note, because of difficulties in filling the cylindrical chamber to produce a saturated soil specimen for testing at water contents around the PL on account of the material's stiff consistency, it is common practice to perform the testing over a range of higher water contents and then to use extrapolation for interpolation of values associated with lower (in this case the PL) water content (see the review papers by O'Kelly (2013, 2021b) and O'Kelly et al. (2018)).

Hence, the presented power-based extrusion methodology determines that, for the TCD extrusion apparatus and die-orifice combinations, the values of the LL_FC and PL could be determined as the water contents corresponding to Δt (= $\Delta x/\bar{v}$) of 10 and 30 s, respectively, as established from interpolation (or extrapolation) of the best-fit regression lines fitted to the experimental data points in a Log Δt vs. water content plot.

4 DEMONSTRATION OF CONSISTENCY LIMITS DETERMINATIONS USING PROPOSED POWER-BASED EXTRUSION APPROACH

Figure 6 presents experimental data from testing of the fine fraction of a Dublin Brown Boulder Clay sample that demonstrates the implementation of the proposed power-based extrusion methodology for consistency limits determinations. The soil investigated had an LL_FC of 34.6% (30°–80 g cone) and Atterberg PL of 18.9%, determined in accordance with BS EN ISO 17892-12:2018+A1:2021 (2021), from which the soil is classified as clay of low plasticity (CL). All the presented testing was performed by an independent experienced operator. Some noise (evident in the experimental data) can be attributed to apparatus friction due to fabrication limitations. Unlike in Figure 6(a), where the LL is within the range of the four measurements, the soil was not tested in the range where the PL was found (owing to the soil's stiff consistency that made it difficult to prepare a saturated test specimen); thus, the associated value was extrapolated using linear regression (see Figure 6(b)).

Overall, it could appear that for this particular test soil, good agreement is found between the standard consistency limits and those derived using the proposed power-based extrusion methodology, especially for the LL parameter. While this could be expected for LL_FC determination, as explained in the next section, this generally would not be the case for Atterberg PL when investigating a range of different fine-grained soils.

5 DISCUSSION: CRITICAL ASSESSMENT OF POWER-BASED EXTRUSION METHODOLOGY FOR CONSISTENCY LIMITS DETERMINATIONS

The hypothesis is that for a given extrusion apparatus and die-orifice combination, specific values of power [J/s] can be assigned to the consistency limits of fine-grained soils. With the deformation work given by the area under the p_e vs. Δx curve, and for the p_e (F_e) magnitude remaining approximately constant throughout the extrusion process, the proposed power-based extrusion approach is essentially a strength-based method, as explained previously in the paper by O'Kelly (2019). Hence, the power-based methodology can be expected to produce good experimental agreement with (i.e., comparable results as obtained by) the LL_{FC}, since the latter is also a strength-based parameter (O'Kelly et al., 2018). However, this would generally not be expected for Atterberg's PL, since different fine-grained soils invariably mobilise different s_{ur} at their Atterberg PL water contents (Haigh et al., 2013; O'Kelly, 2013; O'Kelly et al., 2018, 2022), and hence different p_{e} $(= s_{\mathrm{ur}}/A_{\mathrm{o}})$, and also different $p_{\mathrm{e}}/s_{\mathrm{ur}}$ (O'Kelly, 2019, 2021a) at their Atterberg PL water contents. Furthermore, different fine-grained soils invariably have different toughness at their Atterberg PL water contents (Barnes, 2009, 2013a, 2013b; Moreno-Maroto and Alonso-Azcárate, 2018; O'Kelly, 2019; O'Kelly et al. 2022). Typically, at (just above) Atterberg's PL, silty and sandy soils have slight toughness, whereas low to medium plasticity soils (e.g., silty clays) have medium toughness, and high plasticity clay soils have high toughness. For instance, employing a thread-rolling device developed to measure soil toughness, Barnes (2013a) presented results for many different cohesive soils that showed the toughness at their Atterberg PL water contents can vary over a wide range.

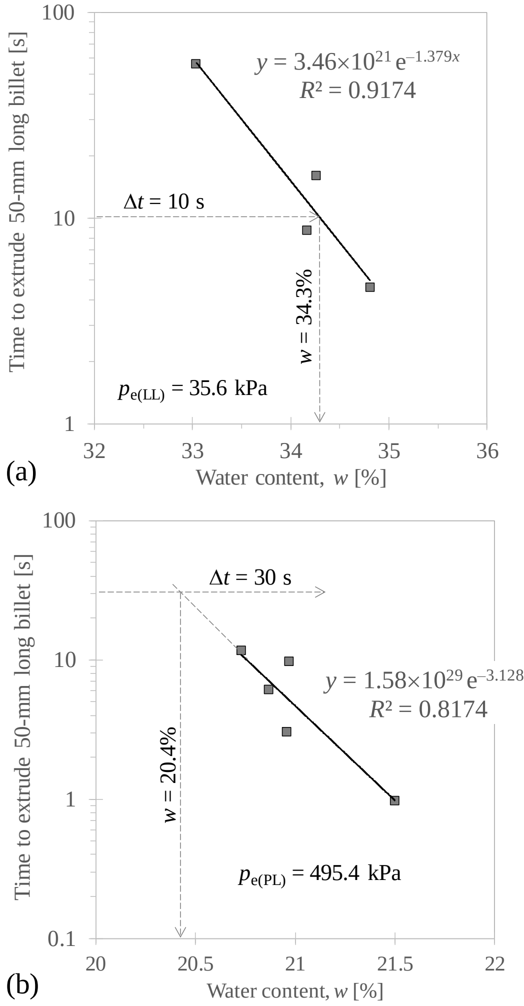


Figure 6. Consistency limits determinations for fine fraction of Dublin Brown Boulder Clay (LL_{FC} = 34.6% and Atterberg's PL = 18.9%) using proposed power-based approach and TCD extrusion apparatus: (a) liquid limit; (b) plastic limit.

Since Atterberg's PL (i.e., the water content at which soil becomes brittle, as determined using the standard thread-rolling method) does not relate to a defined s_{ur} magnitude (Haigh et al., 2013; O'Kelly et al., 2018, 2022; O'Kelly, 2021b), the power-based extrusion methodology is clearly not appropriate for defining the Atterberg PL condition (O'Kelly et al., 2022). However, as a strength-based method, the proposed power-based methodology would be suited for determination of a PSL parameter. Using equation (1), after Johnson (1957), the s_{ur} magnitude for soil direct-extruded using the TCD extrusion apparatus and methodology can be related to the steady-state extrusion force F_{e} (ignoring rate effects). Considering the presented TCD extrusion apparatus and power-based approach for consistency limits determinations, undrained strengths of s_{ur} = 3.5 kPa (F_{e} of ~34.2 N) and 151 kPa (F_{e} of ~476.6 N) can be associated with the LL_{FC} and deduced PSL, respectively. It is noted that the s_{ur} of 151 kPa (for the PSL defined in the present study) fits nicely with the average s_{ur} of 152 kPa (standard deviation of 89 kPa) deduced by Haigh et al. (2013) in analysing data of s_{ur} at the Atterberg PL water contents for 71 different fine-grained soils.

$$s_{\mathrm{ur}} = \frac{2\,F_{\mathrm{e}}}{\pi D^2\left[a + b\ \ln R + \frac{L}{D}\right]} \tag{1}$$

where R = extrusion ratio; D and L = cylindrical chamber's inner diameter and depth, respectively; a and b = empirical coefficients dependent on the die angle (for 90° die angle of the TCD cylindrical chamber, a = 0.8 and b = 1.5 (Johnson, 1957)).

6 CONCLUSIONS AND RECOMMENDATIONS

This paper presented the TCD extrusion apparatus and proposed power-based methodology for determination of the consistency limits of fine-grained soils. The methodology was demonstrated for testing of one soil, and involved an extrapolation of the results (at PL). It was explained that the methodology can essentially be viewed as strength-based, and would be appropriate for determination of the LL (i.e., LL_{FC}) and a PSL; the latter based on a mobilised s_{ur} of ~151 kPa. However, as it is strength-based, the proposed approach cannot be used to determine Atterberg's PL (i.e., the water content at the plastic–brittle transition point), which is definitively established using the standard thread-rolling test (Haigh et al., 2013; O'Kelly et al., 2018, 2022). Considering the presented prototype, various recommendations are made for developing an improved extrusion apparatus, as follows:

- For the power calculations, it would be better to consider a ram displacement Δx that does not involve the ram entering the 'dead' material zone of the cylindrical chamber.
- While the s_{ur} of 3.5 kPa at LL_{FC} could be deemed acceptable, the extrusion apparatus and method can be refined to achieve an s_{ur} of ~ 1.7 kPa, this value being generally associated with the (30°–80 g cone) LL_{FC} water content (O'Kelly et al., 2018; O'Kelly, 2021b).
- There might be scope to adjust the extrusion apparatus and pressures to allow a relatively small range of extrusion velocities ($\bar{v}$) for testing at water contents close to the consistency limits (LL_{FC}).

Finally, it is hypothesised that the power-based extrusion methodology could potentially serve as an alternative means of classifying fine-grained soils (based on the power magnitudes required to cause extrusion at their Atterberg PL water contents). Further research is merited on this aspect.

ACKNOWLEDGEMENTS

Eoin Dunne performed the extrusion (results presented in Figure 6) and consistency limits testing for the Dublin Boulder Clay. Seyedmasoud Manafighorabaei (M.S.G. Manafi) was in receipt of a Postgraduate Research Scholarship award from Trinity College Dublin (2015–2017) during the period of his MSc research.

ABBREVIATIONS

LL	Liquid limit
PL	Plastic limit
PSL	Plastic strength limit

NOTATION

a	Empirical extrusion coefficient
A_f	Die orifice area
A_o	Bore cross-sectional area of cylindrical chamber
b	Empirical extrusion coefficient
D	Inner diameter of cylindrical chamber
F_e	Extrusion force
I_L	Liquidity index
L	Inner depth of cylindrical chamber
LL_{FC}	Liquid limit determined by fall-cone test
p_e	Extrusion pressure
$p_{\mathrm{e(LL)}}$	Extrusion pressure for liquid-limit water content
$p_{\mathrm{e(PL)}}$	Extrusion pressure for the plastic strength limit
P	Power (= $W/\Delta t$)
$P_{\mathrm{(LL)}}$	Power value assigned for liquid-limit water content
$P_{\mathrm{(PL)}}$	Power value assigned for plastic strength limit
PL_x	Plastic strength limit defined by x-fold increase in undrained strength from fall-cone liquid limit water content
R	Extrusion ratio ($= A_\mathrm{o}/A_\mathrm{f}$)
s_u	Undrained shear strength
s_ur	Remoulded undrained shear strength
$\bar{v}$	Average ram velocity ($= \Delta x/\Delta t$)
W	Work done (= $F\,\Delta x$)
Δt	Time period of extrusion
Δx	Ram displacement

REFERENCES

[1] Atterberg A (1911) Die plastizität der tone. *Internationale Mitteilungen der Bodenkunde* 1: 4–37. (In German)

[2] Barnes GE (2009) An apparatus for the plastic limit and workability of soils. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* 162(3): 175–185, https://doi.org/10.1680/geng.2009.162.3.175

[3] Barnes GE (2013a) An apparatus for the determination of the workability and plastic limit of clays. *Applied Clay Science* 80–81: 281–290, https://doi.org/10.1016/j.clay.2013.04.014

[4] Barnes GE (2013b) *The Plastic Limit and Workability of Soils*. PhD thesis, University of Manchester, Manchester, UK.

[5] BS EN ISO 17892-12:2018+A1:2021 (2021) *Geotechnical investigation and testing. Laboratory testing of soil. Determination of liquid and plastic limits*. BSI, London, UK.

[6] Haigh SK, Vardanega PJ and Bolton MD (2013) *The plastic limit of clays*. Géotechnique 63(6): 435–440, https://doi.org/10.1680/geot.11.P.123

[7] Johnson W (1957) The pressure for the cold extrusion of lubricated rod through square dies of moderate reduction at slow speeds. *Journal of the Institute of Metals* 85: 403–408.

[8] Kayabali K, Akturk O, Fener M, Dikmen O and Harputlugil FH (2015) Revisiting the Bjerrum's correction factor: use of the liquidity index for assessing the effect of soil plasticity on undrained shear strength. *Journal of Rock Mechanics and Geotechnical Engineering* 7(6): 716–721, https://doi.org/10.1016/j.jrmge.2015.07.003

[9] Manafighorabaei S (2017) *Soil Plasticity Determination Using Manafi Method and Apparatus*. MSc thesis, University of Dublin, Trinity College Dublin, Dublin, Ireland, http://hdl.handle.net/2262/81676

[10] Manafi MSG, Deng A, Taheri A, Jaksa MB and HB N (2022) Determining soil plasticity utilizing Manafi method and apparatus. *Geotechnical Testing Journal* 45(4): 797–818, https://doi.org/10.1520/GTJ20210235

[11] Moreno-Maroto JM and Alonso-Azćarate J (2018) What is clay? A new definition of "clay" based on plasticity and its impact on the most widespread soil classification systems. *Applied Clay Science* 161: 57–63, https://doi.org/10.1016/j.clay.2018.04.011

[12] O'Kelly BC (2013) Atterberg limits and remolded shear strength–water content relationships. *Geotechnical Testing Journal* 36(6): 939–947, https://doi.org/10.1520/GTJ20130012

[13] O'Kelly BC (2019) Reappraisal of soil extrusion for geomechanical characterisation. *Geotechnical Research* 6(4): 265–287, https://doi.org/10.1680/jgere.19.00006

[14] O'Kelly BC (2021a) Discussion of "Strength and consolidation characteristics for cement stabilized cohesive soil considering consistency index" by Ahmed F. Zidan, published in Geotechnical and Geological Engineering, https://doi.org/10.1007/s10706-020-01367-6. *Geotechnical and Geological Engineering* 39(6): 4659–4662, https://doi.org/10.1007/s10706-021-01763-6

[15] O'Kelly BC (2021b) Review of recent developments and understanding of Atterberg limits determinations. *Geotechnics* 1: 59–75, https://doi.org/10.3390/geotechnics1010004

[16] O'Kelly BC, Vardanega PJ and Haigh SK (2018) Use of fall cones to determine Atterberg limits: a review. *Géotechnique* 68(10): 843–856, https://doi.org/10.1680/jgeot.17.R.039

[17] O'Kelly BC, Moreno-Maroto JM and Alonso-Azćarate J (2022) Discussion of "Determining soil plasticity utilizing Manafi method and apparatus" by Masoud S. G. Manafi, An Deng, Abbas Taheri, Mark B. Jaksa, and Nagaraj HB. *Geotechnical Testing Journal* (In Press).

[18] O'Kelly BC, Vardanega PJ and Haigh SK (2022) Discussion of "Mohajerani method: tool for determining the liquid limit of soils using fall cone test results with strong correlation with the Casagrande test" by E. Hrubesova, B. Lunackova and M. Mohyla [Engineering Geology 278 (2020) 105852]. *Engineering Geology* 302: 106623, https://doi.org/10.1016/j.enggeo.2022.106623

[19] Sivakumar V, O'Kelly BC, Henderson L, Moorhead C, Chow SH and Barnes GE (2016). Discussion: Measuring the plastic limit of fine soils: an experimental study. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* 169(1): 83–85, https://doi.org/10.1680/jgeen.15.00068

[20] Timár A (1974) Testing the plastic properties of cohesive- and intermediate-type soils by extrusion. *Acta Technica Academiae Scientiarum Hungaricae* 76(3–4): 355–370.

[21] Whyte IL (1982) Soil plasticity and strength — a new approach using extrusion. *Ground Engineering* 15(1): 16–24.

AUTHOR BIOGRAPHY

Dr. Brendan O'Kelly has worked in academia and geotechnical engineering practice since graduating as a civil engineer from UCD in 1992. In 2001, he joined the Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, where he is presently an Associate Professor and Fellow of Trinity College Dublin (FTCD, 2010). His main research interests are soil consistency limits, ground improvement, geotechnics of water- and wastewater-treatment sludges, and the geomechanical behaviour/properties of peat and other highly organic soils, on which he has authored more than 120 refereed journal papers. He is an Associate Editor for the journals *Environmental Geotechnics* (ICE) and *Geotechnics* (MDPI), and is a serving council member of the International Society of Environmental Geotechnology.