Proceedings of the XVI ECSMGE
Geotechnical Engineering for Infrastructure and Development
ISBN 978-0-7277-6067-8

doi:10.1680/ecsmge.60678

Determination of consistency limits of clay by means of extrusion tests

Détermination des limites de consistance d'argiles au moyen d'essais d'extrusion

R.D. Verástegui-Flores[*1], G. Di Emidio[2]

[1] *iMMC, Université catholique de Louvain, Louvain-la-Neuve, Belgium*
[2] *Laboratory of Geotechnics, Ghent University, Ghent, Belgium*

[*] *Corresponding Author*

ABSTRACT The liquid limit of clay is commonly determined through the Casagrande test or the fall-cone test, while the plastic limit is determined through the hand rolling method. The greatest issue with some of these techniques is their low repeatability and operator dependency. In order to minimize those issues, an indirect-extrusion based technique was evaluated as an alternative method to determine both consistency limits. The experimental work was carried out on mixtures of kaolin and bentonite to cover a wide range of plasticity. The results suggested that there is a specific extrusion pressure linked to each consistency limit and that the results are repeatable. The liquid limit obtained through the extrusion method closely matches the results of the fall-cone test. Similarly, the plastic limit out of extrusion closely matches the results of the hand rolling method.

RÉSUMÉ La limite de liquidité de l'argile est généralement déterminée par l'essai de Casagrande ou l'essai au cône, alors que la limite plastique est déterminée par la méthode au rouleau. Le principal problème avec certaines de ces techniques est leur faible répétabilité ainsi que l'influence de l'opérateur. Afin de minimiser ces problèmes, une méthode d'extrusion indirecte a été évaluée comme une méthode alternative pour déterminer les limites de consistance. Le travail expérimental a été effectué sur des mélanges de kaolin et bentonite pour couvrir une large gamme de plasticité. Les résultats suggèrent l'existence d'une pression d'extrusion spécifique liée à chaque limite de consistance et que les résultats sont répétables. La limite liquide obtenue par le procédé d'extrusion correspond étroitement aux résultats de l'essai au cône. De même, la limite plastique obtenue de l'essai d'extrusion indirecte correspond étroitement aux résultats de la méthode conventionnelle au rouleau.

1 INTRODUCTION

In soil mechanics, consistency is a fundamental parameter for the classification of fine-grained soil. Consistency can be classified as liquid, plastic, semi-solid and solid, each associated with a rheological behavior. The consistency of clay is liquid at high water contents and changes from liquid to solid as the water content decreases.

The most relevant consistency indexes are the liquid limit (w_L) and the plastic limit (w_P). w_L is the water content of a sample at the boundary between liquid and plastic behavior, whereas w_P is the water content of a sample at the boundary between plastic and semi solid behavior. w_L is determined through the Casagrande cup test or the fall-cone test, while w_P is determined through the hand rolling method. The greatest issue with some of these techniques is their low repeatability and operator dependency. In order to minimize those issues, an indirect extrusion technique was evaluated as an alternative to determine both, w_L and w_P.

Extrusion is the mechanical production process by which a block of a material (billet) is reduced in cross section by forcing it to flow through a die orifice under a compression stress. The two basic types of extrusion processes are direct and indirect extrusion. Fig. 1a shows the principle of direct extrusion where a billet is placed in a container and it is pushed through a die by applying a ram pressure. The direction of sample flow and ram travel is the same. Under direct extrusion, the extrusion pressure vs. ram displacement curve most commonly has the form shown in Fig. 1a. Initially, the extrusion pressure rises rapidly up to a peak value. Then, as extrusion initiates, the pressure decreases as the frictional component at the container wall decreases. Finally, at the billet's end, the pressure increases once more as the billet becomes short and the material shows higher resistance to flow. Under indirect extrusion, also called reverse extrusion, the die moves against the sample, which is in a stationary container (Fig. 1b). The directions of sample flow and die travel are opposite. The advantage of indirect extrusion is that no frictional forces are mobilized at the container wall and therefore the extrusion pressure primarily depends on the properties of the sample.

The concept of extrusion has been applied for the rheological characterization of different materials such as food, ceramics, etc. (e.g. Cheyne et al., 2005; Göhlert & Uebel , 2009). The extrusion technique was probably first applied for geotechnical purposes by Whyte (1982); however, his work focused on establishing a relationship between undrained shear strength, extrusion pressure and water content.

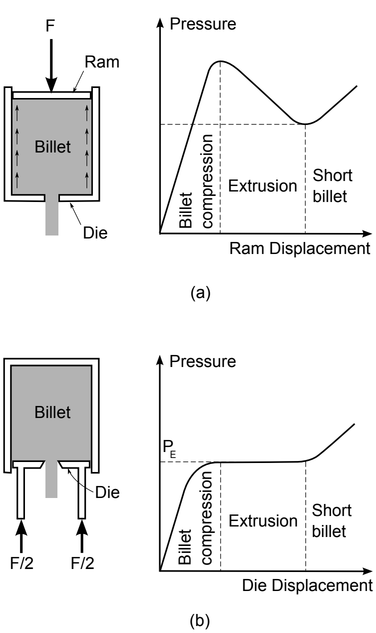


Figure 1. Extrusion process: (a) direct (b) indirect

Kayabali & Tufenkci (2010) investigated indirect extrusion to determine the consistency limits of different types of natural soil with plasticity indexes $I_P <$ 50, taking as a reference the consistency tests described by the ASTM D 4318 (2010). They reported a correlation with significant dispersion probably due to the different shearing conditions that the clay samples undergo in the Casagrande cup and in the indirect extrusion setup, and probably also due the impact of side friction in their testing setup.

The aim of this paper is to investigate whether it is possible to establish a stronger correlation for the determination of consistency limits of different clay samples over a wider range of plasticity through the indirect extrusion technique by minimizing all possible sources of dispersion. At the same time, the results are compared to the test methods described in ASTM D 4318 (2010) and BS 1377-2 (1990).

2 MATERIALS

The experimental work was carried out on mixtures of kaolin (K) and bentonite (B) to cover a wide range of plasticity (e.g. 100%K, 80%K+20%B, 60%K+40%B, 40%K+60%B, 20%K+ 80%B and 100%B). Some properties are given in table 1.

Kaolin and bentonite were first mixed dry at the specific ratios. Subsequently, deionized water was added to the mixtures to achieve various water contents. Water and clay were mixed in a dough mixer for about 15 minutes. Then, the wet samples were stored in air-tight containers (in a conditioned room at about 20ºC) at least for one day before testing.

The testing program on these samples included the execution of conventional tests to evaluate w_L and w_P and more importantly, the development and evaluation of an indirect-extrusion method. The outcome of the conventional tests serves as a reference for the calibration of the extrusion method.

Table 1. Properties of the clay materials

Property	Kaolin	Bentonite
Specific gravity	2.64	2.52
Liquid limit, %	53.2	374.7
Plastic limit, %	31.0	62.9
Swell index, ml/2g	3.5	18.0
CEC, meq/100g	1.4	73.8

3 METHODS

3.1 Conventional methods for the liquid limit

LL may be determined through the Casagrande cup test (ASTM D 4318, 2010) or the fall cone test (BS 1377-2, 1990). The repeatability of the Casagrande cup method is known to be affected by operator judgment (Whyte, 1982; Özer, 2009). On the contrary, repeatability is not an issue for the fall cone test, however the outcome of this test has to be carefully assessed as it will produce results for all soil types including non-plastic soils, giving a wrong representation of plasticity (Prakash & Sridharan, 2006). Moreover, the Casagrande cup and fall cone test do not produce the same results (Wasti, 1987; Schmitz et al., 2004; Prakash & Sridharan, 2006; Lee & Freeman, 2009; Özer, 2009). In general, good agreement is observed for soils within an approximate range of 0% < w_L < 70%. Outside this range, the fall cone test produces lower w_L values.

3.2 Conventional methods for the plastic limit

w_P is evaluated out of the standardized hand rolling method (ASTM D 4318, 2010; BS 1377-2, 1990). However, a few fall-cone based methods are available in the literature as well (e.g. Wood & Wroth, 1978; Wasti, 1987; Feng, 2004; Lee & Freeman, 2009). In this research, the method proposed by Feng (2004) was followed in addition to the hand method. Here, four fall cone measurements are carried out to obtain cone penetrations ranging from 10 mm to 3 mm. Then, w_P is determined, through linear extrapolation in a bi-logarithmic chart, as the water content corresponding to a cone penetration of 2 mm.

3.3 Indirect extrusion testing method

The equipment used for the indirect extrusion tests consists of a load frame provided with a platen that moves at adjustable constant rates, an indirect extrusion device (Fig. 2), a load cell with a capacity of 2 kN and a linear displacement transducer. The indirect extrusion device consists of a steel container and a steel extrusion die. The extrusion die rests on top of a cylindrical tube and a footplate. The die orifice with diameter *d* has a conical shape to minimize friction between the extruded sample and the die.

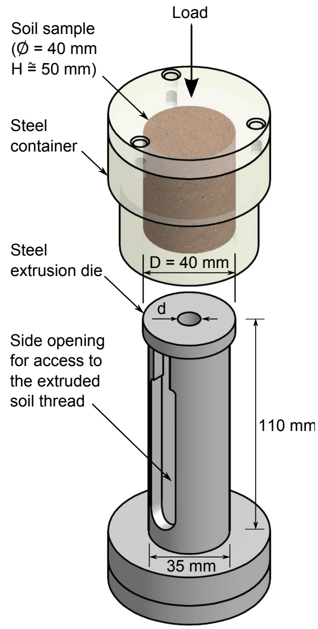


Figure 2. Indirect extrusion device used in this research.

During extrusion testing, the die displacement and the extrusion load (F_E) are continuously recorded. The extrusion pressure P_E is then evaluated out of the steady-state portion of the measured F_E vs. die displacement curve (e.g. Fig. 1b) through:

$$P_E = \frac{F_E}{A} \qquad (1)$$

where A is the cross section of the sample container. P_E not only depends on the clay water content, but also on the die displacement rate (v) and on the extrusion factor (r). The extrusion factor is defined here as $r = D/d$, where D is the diameter of the sample container and d is the diameter of the die orifice.

A test is started as soon as the die is set to travel against the clay sample. For the sake of simplicity, it is desired that all tests are performed making use of a single extrusion factor and a single die displacement rate that produce representative and repeatable data. So, a choice was made based on a series of experiments to evaluate the impact of these factors. The die with $r = 4$ and a rate $v = 4$ mm/min were selected as the most suitable for all further indirect extrusion tests in this research.

4 RESULTS AND DISCUSSION

The consistency limits out of conventional tests on kaolin/bentonite mixtures are summarized in Fig 3. As expected, both w_L and w_P increase with increasing bentonite content. In agreement with literature, w_L out of fall cone test is lower than Casagrande cup results for high w_L values. w_P out of the hand method and the fall cone method are in good agreement.

The testing program with the indirect extrusion technique included, first, the determination of the characteristic steady-state extrusion pressures corresponding to w_L and w_P states ($P_{E(LL)}$ and $P_{E(PL)}$ respectively) on reference samples. Next, it followed the verification of such values as indicators of consistency in other soil samples.

For the determination of $P_{E(LL)}$, a kaolin sample was taken as reference. w_L of kaolin out of Casagrande and fall cone tests are very similar, $w_{L(Cas)}$ = 53.2% and $w_{L(FC)}$ = 55.6%, respectively. Then, a remolded sample of kaolin was prepared at a water content equal to the average LL. Next, several indirect extrusion tests were carried out on this material to evaluate the repeatability of the outcome (Fig. 4a). As expected, beyond the onset of extrusion, the extrusion pressure reaches a constant value, which indicates steady-state flow of the soil sample. The evaluation of the steady-state extrusion pressure was straightforward and it showed little dispersion with an average value of $P_{E(LL)}$ = 23.6 kPa corresponding to the liquid limit state.

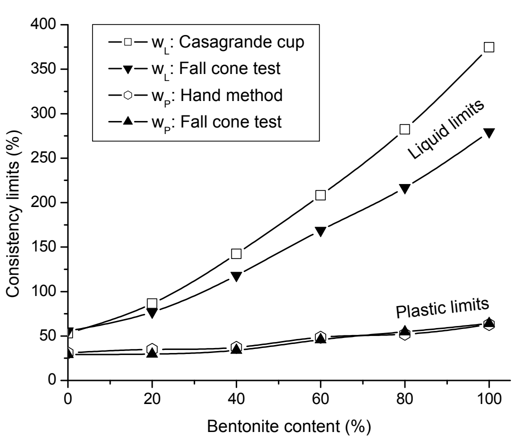
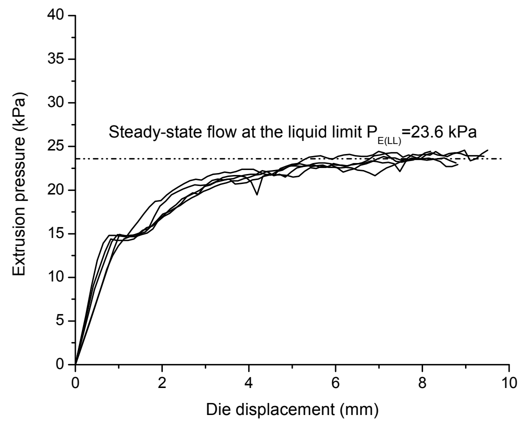
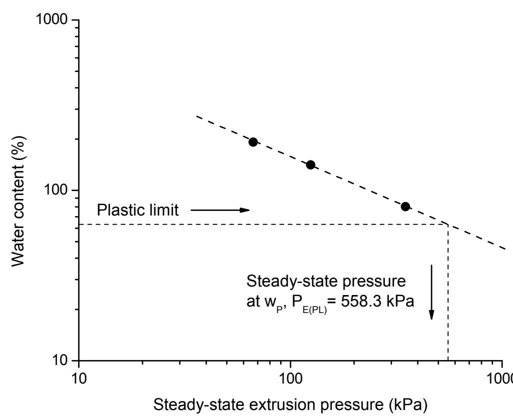


Figure 3. w_L and w_P through conventional methods.



(a)



(b)

Figure 4. Evaluation of the steady-state extrusion pressure at (a) liquid limit state (b) plastic limit state.

For the determination of $P_{E(PL)}$, a bentonite sample was taken as reference. But, unlike samples at w_L, samples at w_P are hardly workable. Therefore it was opted for performing extrusion tests at water contents slightly higher than w_P and evaluating $P_{E(PL)}$ out of regression and extrapolation as it is done in the fall-cone method for the determination of w_P (Feng, 2004). Indirect extrusion tests were carried out on samples at various water contents (every tests was repeated twice). The relationship between water content (w) and the steady-state extrusion pressure was observed to be highly non linear in a semi-logarithmic chart. However, when plotting the same points in a bi-logarithmic chart, a well-defined linear trend could be observed. Fig. 4b shows the resulting regression line with a coefficient of determination R^2 = 0.999 indicating an almost perfect match. Finally, the extrusion pressure corresponding to w_P of the reference sample ($w_{P(hand)}$ = 62.9%) was determined as $P_{E(PL)}$ = 558.3 kPa, out of extrapolation.

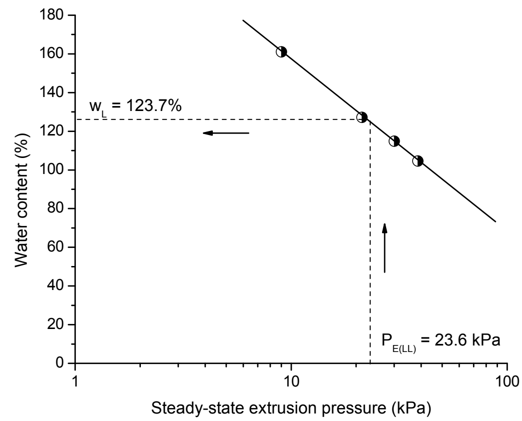
Next, to verify the validity of $P_{E(LL)}$ and $P_{E(PL)}$ as indicators of consistency, indirect extrusion tests were carried out on the rest of the samples consisting of mixtures of kaolin and bentonite. The followed procedures are described below.

For the determination of the liquid limit, 3 to 4 indirect extrusion tests are carried out on samples at different water contents (w) to produce P_E values within a range of 10 kPa to 50 kPa approximately. The relationship between w of the extruded soil thread and P_E should show a rather linear trend in a semi-logarithmic chart. Then, w_L is defined through linear interpolation as the water content corresponding to $P_{E(LL)}$ = 23.6 kPa.

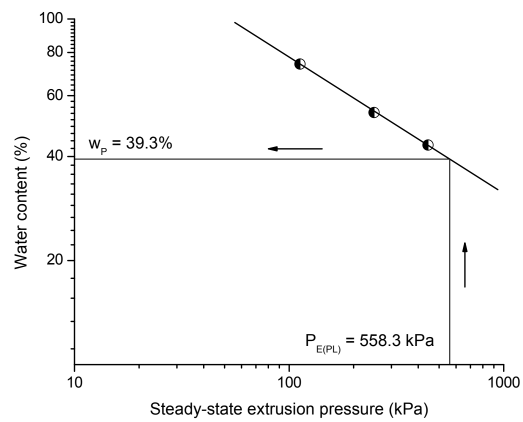
For the determination of plastic limit, 3 to 4 indirect extrusion tests are carried out on samples at different water contents to produce P_E values within a range of 100 kPa to 400 kPa approximately. Then, the relationship w vs. P_E is plotted in a bi-logarithmic chart and finally, w_P is defined through linear extrapolation as the water content corresponding to $P_{E(PL)}$ = 558.3 kPa. These procedures are illustrated in Fig. 5 for a mixture 40% bentonite & 60% kaolin.

No issues were encountered, except for the determination of w_P of kaolin. Here, the extrusion pressure induced consolidation in the specimen (dewatering through the die orifice) and a steaty-state extrusion pressure could not be interpreted. However, this issue was attributed to the specific properties of the industrially purified kaolin sample used in this research. In fact, test on other samples (e.g. Boom clay) with similar w_P but different mineralogy did not show any issues. Moreover, Kayabali & Tufenkci (2010) tested about 30 natural soil samples (with 83% > w_L > 26% and 47% > w_P > 18%) through an extrusion-based technique without reporting dewatering issues.

Finally, Fig. 6 summarizes and compares the results of indirect extrusion tests with conventional tests. It was found that w_L out of indirect extrusion is lower than w_L out of Casagrande tests.



(a)



(b)

Figure 5. Example of determination of (a) liquid limit (b) plastic limit of a sample consisting of 40% bentonite and 60% kaolin

However, a very good match was observed with w_L out of fall cone tests. A reason for this difference may be that both, the fall cone test and the indirect extrusion test, subject the sample to sustained loading, whereas a sample in the Casagrande cup is subjected to instantaneous loading. Because strength (especially for high plasticity clays) is sensitive to rate effects (Diaz-Rodriguez et al., 2009), the sample responds to instantaneous loading with a higher strength magnitude. Therefore, Casagrande tests may allow for higher water contents on the sample.

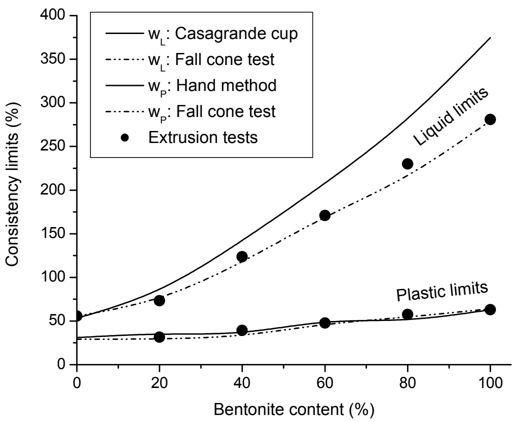


Figure 6. Consistency limits from conventional and extrusion tests

Moreover, w_P out of indirect extrusion shows good agreement with the results obtained out of conventional methods.

5 CONCLUSIONS

An indirect-extrusion method was evaluated as an alternative to determine w_L and w_P. Experimental work with this technique was carried out on mixtures of kaolin and bentonite to cover a wide range of plasticity. The samples were tested in an indirect extrusion device with an extrusion factor $r = 4$ and at a die displacement rate of $v = 4$ mm/min.

During an indirect extrusion test, the mobilized extrusion pressure is continuously monitored vs. die displacement. Out of these measurements a steady-state extrusion pressure (P_E) is evaluated. For the determination of w_L, the test is repeated 3 to 4 times on samples at various water contents to produce P_E values within 10 kPa to 50 kPa. Similarly, for the determination of w_P, the test is repeated 3 to 4 times to produce P_E values within 100 kPa to 400 kPa. Then, w_L is defined through linear interpolation in a semi-logarithmic chart as the water content corresponding to a characteristic extrusion pressure of $P_{E(LL)} = 23.6$ kPa, whereas w_P is defined through linear extrapolation in a bi-logarithmic chart as the water content corresponding to a characteristic extrusion pressure of $P_{E(PL)} = 558.3$ kPa.

w_L out of indirect extrusion is lower than w_L out of Casagrande tests; however, a very good match was observed with results out of fall cone testing. Moreover, w_P estimated out of indirect extrusion shows good agreement with the results of conventional tests. An important advantage of the indirect extrusion technique though, is that it is able to produce both consistency limits while operator judgment plays a less important role.

REFERENCES

ASTM D 4318, 2010. Standard test methods for liquid limit, plastic limit and plasticity index of soils, ASTM International.

BS 1377-2: 1990. Methods of test for soils for civil engineering purposes. Classification tests, British Standards Institution.

Cheyne, A. Barnes, J. & Wilson, D.I. 2005. Extrusion behaviour of cohesive potato starch pastes: I. Rheological characterisation. *Journal of Food Engineering* **66**, 1-12.

Diaz-Rodriguez, J.A. Martinez-Vasquez, J.J. & Santamarina, J.C. 2009. Strain rate effects in Mexico City soil. *Journal of Geotechnical and Geoenvironmental Engineering* **135**, 300-305.

Feng, T.W. 2004. Using small ring and a fall cone to determine the plastic limit. *Journal of Geotechnical and Geoenvironmental Engineering* **130**, 630-635.

Göhlert, K. & Uebel, M. 2009. Test methods for plasticity and extrusion behaviour. *Extrusion in Ceramics*, (Ed. Händle, F.), Engineering Materials and Processes. Springer.

Kayabali, K. & Tufenkci, O.O. 2010. Determination of plastic and liquid limits using the reverse extrusion technique. *Geotechnical Testing Journal* **33**, 14-22.

Lee, L.T. & Freeman, R.B. 2009. Dual-weight fall cone method for simultaneous liquid and plastic limit determination. *Journal of Geotechnical and Geoenvironmental Engineering* **135**, 158-161.

Özer, M. 2009. Comparison of liquid limit values determined using the hard and soft base Casagrande apparatus and the cone penetrometer. *Bulletin of Engineering Geology and the Environment* **68**, 289-296.

Prakash, K. & Sridharan, A. 2006. Critical appraisal of the cone penetration method of determining soil plasticity. *Canadian Geotechnical Journal* **43**, 884-888.

Schmitz, R.M. Schroeder, C. & Charlier, R. 2004. Chemo-mechanical interactions in clay: a correlation between clay mineralogy and Atterberg limits. *Applied Clay Science* **26**, 351-358.

Wasti, Y. 1987. Liquid and plastic limits as determined from the fall cone and the Casagrande methods. *Geotechnical Testing Journal* **10**, 26-30.

Whyte, I.L. 1982. Soil plasticity and strength - a new approach using extrusion. *Ground Engineering* **15**, 16-24.

Wood, D.M. & Wroth, C.P. 1978. The use of the cone penetrometer to determine the plastic limit. *Ground Engineering* **11**, 37-44.