In situ shear resistance measurement of soils by the Phicometer Borehole Shear Test according to the new ISO 22476-16 standard

La mesure in situ de la résistance au cisaillement des sols par l'essai au Phicomètre de cisaillement en forage suivant la nouvelle norme ISO 22476-16

Moulay Idriss Zerhouni[1#], and *Robert* Heintz[2]

[1]*Fondasol, Nanterre, France*
[2]*Eurasol, Luxembourg, Luxembourg*
[#]*Corresponding author: moulay.zerhouni@groupefondasol.com*

ABSTRACT

Since its creation by G. Philipponnat in the mid eighties, thousands of in situ borehole shear tests by the phicometer procedure have been carried out in various soils. The phicometer borehole shear test (PBST) provides a rapid in-situ mean for determining the shear resistance (cohesion and friction angle) using the Phicometer Device. For this in situ test which is covered by the French standard Afnor XP P94-120 since 1997, an international standard, EN ISO 22476-16, has been developed under the aegis of the ISO TC182 technical committee for Geotechnical investigation and testing. The first edition of the EN ISO 22476-16 standard was published in november 2024. The article presents the principle of the test, its main equipment and its implementation in the field. Examples of PBST test results obtained on different types of natural soils as well as special materials such as coarse soils, municipal waste and clinker resulting from waste incineration are presented and commented on.

RESUME

Depuis sa création par G. Philipponnat au milieu des années 1980, des milliers d'essais de cisaillement en forage in situ, par la méthode du phicomètre, ont été réalisés dans divers sols. L'essai de cisaillement en forage au phicomètre (PBST) offre un moyen rapide de déterminer in situ la résistance au cisaillement (cohésion et angle de frottement) à l'aide du dispositif phicomètre. Pour cet essai in situ, couvert par la norme française Afnor XP P94-120 depuis 1997, la norme internationale ISO 22476-16, a été élaborée sous l'égide du comité technique ISO TC182 Reconnaissance et essais géotechniques. La première édition de la norme ISO 22476-16 a été publiée en novembre 2024. Cet article présente le principe de l'essai, ses principaux équipements et sa mise en œuvre sur le terrain. Des exemples de résultats d'essais PBST obtenus sur différents types de sols naturels ainsi que sur des matériaux particuliers tels que des sols grossiers, des déchets ménagers et des mâchefers issus de l'incinération de déchets sont présentés et commentés.

Keywords: Borehole shear test, phicometer, PBST; shear strength, cohesion, friction angle, ISO 22476-16, field testing, MSW.

1. Introduction

The determination of the shear strength of soils is of primary importance in geotechnical investigation and testing of soils. The shear resistance of soils and materials, characterized by the friction angle φ and the cohesion c, represents an important parameter for the geotechnical engineer while studying the stability of construction works and structures in relation with soils and materials. Usually, this resistance is measured in the laboratory using triaxial tests or direct shear tests carried out on field samples and only if sampling, conservation and preparation make it possible to consider the samples as non-remolded and sufficiently representative of the soil in place.

Since the 1960's, some experimental devices have been designed and developed to determine the shear strength directly in situ from tests carried out in boreholes, in different soils at different depths.

The study of the corresponding literature shows that the majority of the existing borehole shear tests are based on the use of probes for applying and maintaining a normal pressure on the walls of the borehole and then to carry out a shear phase by a linear displacement of the probe on the soil against the walls of the borehole. The procedure is then repeated through a multistage increase of the normal pressure to obtain more values relating normal pressure and shear resistance.

This document applies to the borehole shear test using the phicometer procedure, commonly named the phicometer borehole shear test (PBST). This test has been invented and developed by Gérard Philipponnat in the 1980's (Philipponnat 1986).

Between 1986 and 1992, several applied research programs have been conducted to design the apparatus and its components and to develop and optimize a common test procedure that can be used in a majority of soils. Since then PBST tests continue to be carried out currently, for the in situ determination of the shear strength parameters from the test and to derive values for the undrained shear strength and for the drained effective shear resistance parameters (Philipponnat and Zerhouni 1993). The test has been standardized in France since 1997 and a new international EN ISO 22476-16 standard for this test has been developed and published in 2024.

2. Principle of the phicometer borehole shear test

2.1. Description of the phicometer equipment

The phicometer device is described in the EN ISO 22476-16 standard. It includes three principal parts when installed in a phicometer borehole (Fig.1).

- The phicometer probe (10), which consists of a steel hollow cylindrical slotted tube (8) and includes a radially expandable cell (9). A series of annular teeth (Fig. 2) are provided in the central part of the probe to form the cylindrical surface of shearing (8). The initial diameter at rest of the probe (deflated state) is 58 mm. The surface of shearing during the test varies but remains close to 500 cm^2.
- Link and connection devices (7) of the Phicometer probe to the control and measurement equipment located at the ground surface, such as steel rods to connect (5) the probe to the pulling device and a tube line connecting the inflatable cell of the probe to the control unit (CU).
- The pressure and volume control unit CU (1) located at the ground surface which includes a pressure–volume controller to measure the volume of the inflatable cell and control the pressure applied to the ground through the cylindrical surface of shearing of the phicometer probe, two ground support reaction plates (2) and a hollow jack (3) for exerting the pull out shearing effort and a force measuring device (4). The pull out shearing speed is maintained constant to 2 $mm.min^{-1}$ by the speed regulation device (6).

A picture of the phicometer probe is provided in Fig. 2. In this view, the probe shown is partially inflated and the slots of the slotted tube are slightly open. The annular teeth of the shearing zone in the mid height of the probe are also visible.

2.2. Phicometer borehole shear test procedure

The phicometer borehole shear test can be performed in almost all types of soil which can be saturated or not, except very soft fine soils, loose coarse soils, medium hard to very hard rocks and soils with cobbles having particle diameter greater than 150 mm.

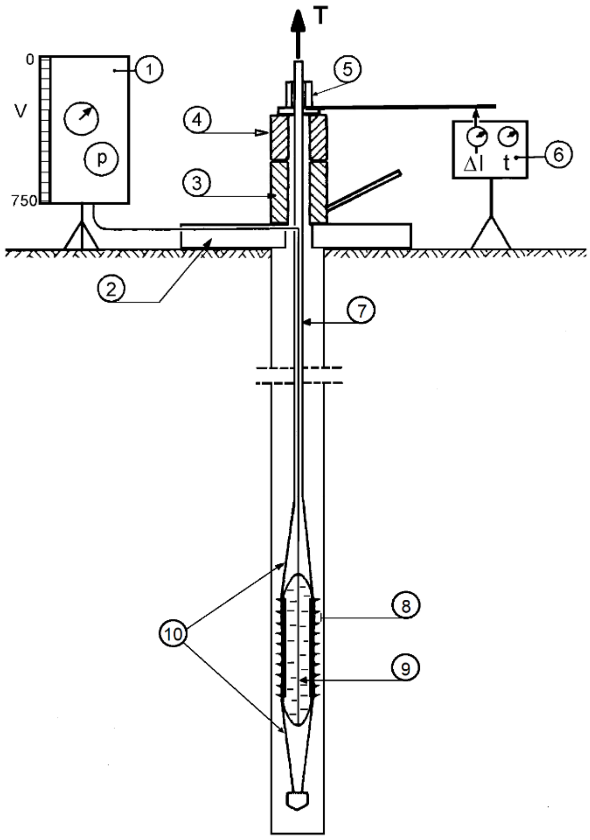

Figure 1. The PBST installation and assembly diagram.

The procedure of the phicometer borehole shear test consists in introducing in a previously made borehole, at a defined depth, the phicometer probe, followed then by two main phases: the teeth insertion phase and the shearing phase.

Figure 2. View of the phicometer probe in a moderately inflated state

The teeth insertion phase consists in inflating the probe by following successive increasing loading stages of constant pressure to penetrate the annular teeth into the material at the wall of the borehole.

The shearing phase is carried out by successive stages of pulling the probe at a constant displacement rate of 2 mm.min^{-1} while maintaining constant, for each stage, the pressure of the probe. The pulling force T and the volume V injected in the probe are measured for each stage along with the pulling displacement.

Up to 8 shearing stages are carried out under successive increasing stages of pressure holds, thus giving the relation between the applied radial pressure p_c and the corresponding shearing resistance τ of the tested material.

The EN ISO 22476-16 standard defines the test procedure and the shearing phase loading program to achieve regarding the strength and type of material.

2.3. Data reduction and calculation of the limit shear stress τ_l

After having determined, by means of a calibration, the relation between the measured volume V and the external diameter d_s of the shear zone of the probe and the relation giving the probe pressure loss, the data reduction of the measurements is carried out as described hereafter, following the parameters defined in Fig.3.

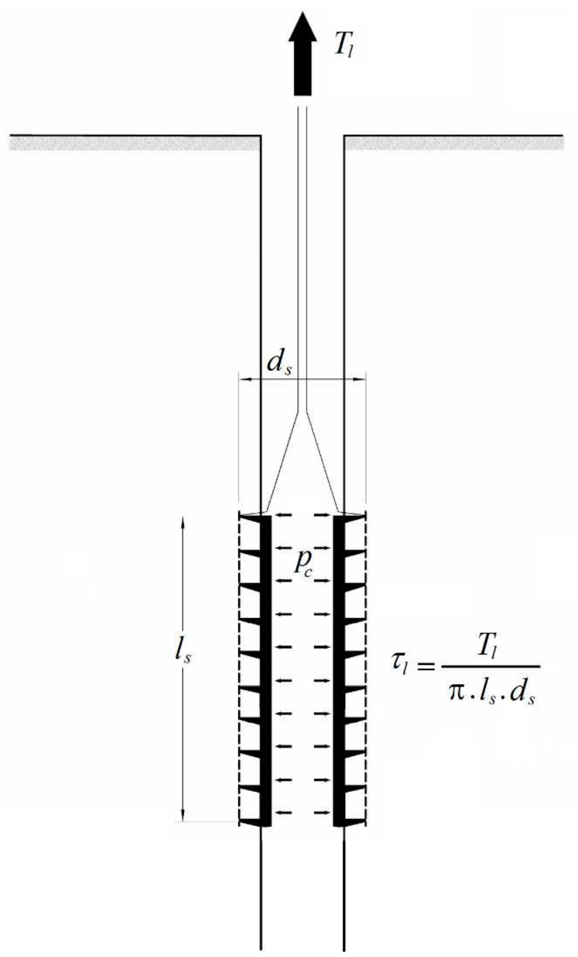

Figure 3. PBST principle and parameters definition.

For each stage of shearing, the values of the conventional limit shear stress of the ground τ_l and the conventional net radial stress p_c, are determined.

The limit shear stress of the ground τ_l corresponds to the maximum value of the pulling force T_l measured during each shear stage, after elimination of any aberrant or non-representative values. The net radial pressure p_c being applied by the probe on the ground is equal to the pressure read with the control unit, increased by the hydrostatic pressure at the test depth and decreased by the pressure loss of the probe for the corresponding injected volume.

2.4. Shear strength parameters φ_i and c_i

In a graph having the radial pressure p_c for X-coordinates and the limit shear stress τ_l for Y-ordinates, the points τ_l (p_c) of all the stages of the shearing phase are represented in Fig. 4a. The shear strength parameters are determined by a linear fitting on the significant and representative points τ_l (p_c) of the graph. The adjusted line represents the Coulomb linear envelope.

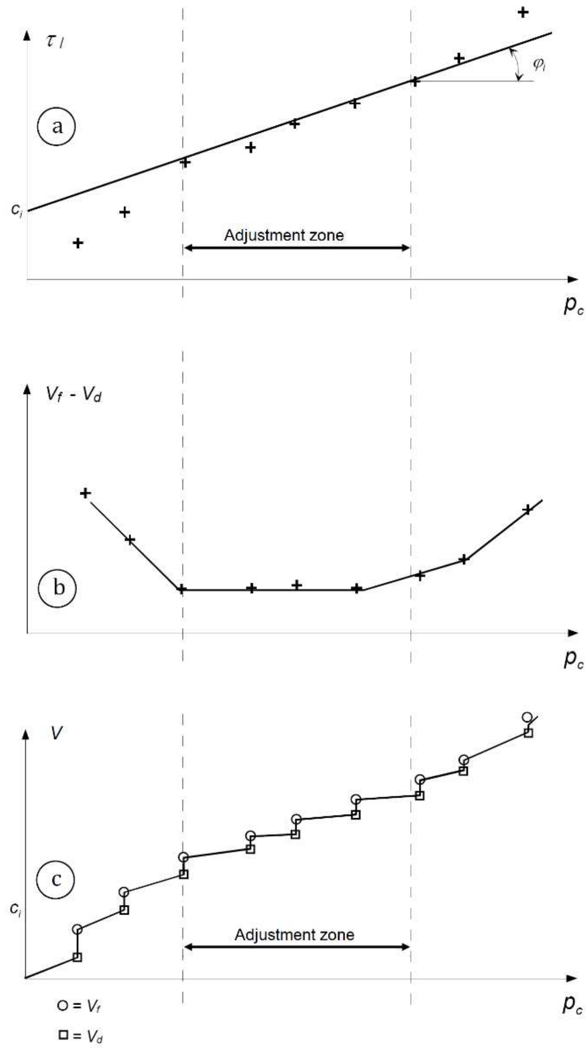

Figure 4. PBST graph results and parameters definition.

The in situ angle of friction φ_i measured by the phicometer borehole shear test is defined by the slope angle of the Coulomb linear envelope. The in situ cohesion c_i, measured by the phicometer borehole shear test is the ordinate at the origin of this linear envelope.

Two other graphs are associated with the shearing curve graph. They represent:

- the creep expansion curve of the probe which represents the difference in volume injected into the probe between the beginning and the end of each stage of the pulling phase (V_f - V_d) against p_c (Fig. 4b);
- the injected volume curve representing the injected volume in the probe V against p_c (Fig. 4c).

These two graphs are used in particular to check the quality of the test and to help determine the adjustment zone to obtain the Coulomb linear envelope.

3. Examples of PBST Test results

3.1. Test results obtained on different types of natural soils

The Figure 5 shows the results obtained from a phicometer borehole shear test carried out at 5 m depth in a compact dense marly fine sand.

Except the two first points in the $\tau(p_c)$ diagram, the experimental measured points follow the same linear coulomb envelope. The linear adjustment on these points gives therefore an in situ friction angle of $\varphi_i = 35°$ as rounded value and no cohesion (c_i = 0 kPa) for this non-cohesive granular soil. The high value of the friction angle is consistent with the sandy nature of the tested soil.

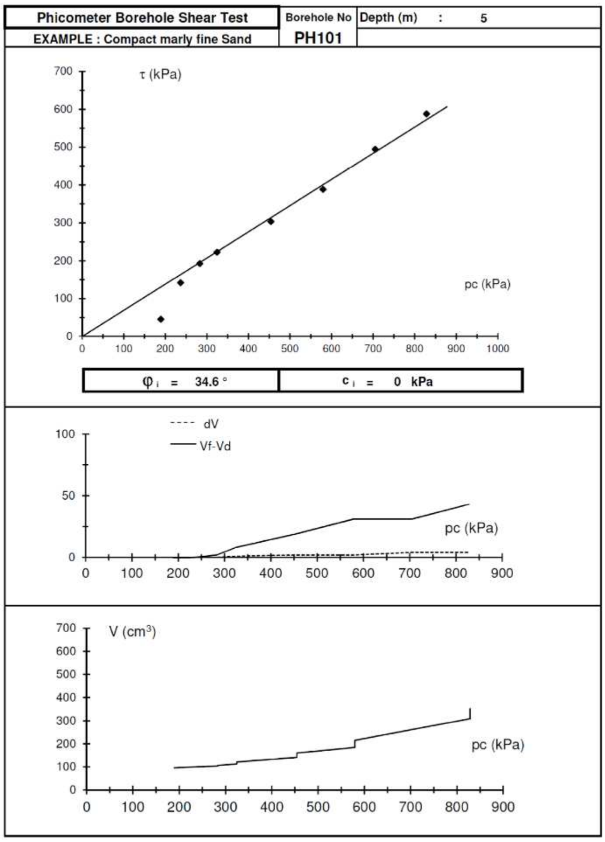

Figure 5. Example of a PBST test results in a compact dense fine sand.

The injected volume curve and the creep expansion curve exhibit a relatively low variation, corresponding to a rather compact stiff soil.

Figure 6 shows the results obtained from a phicometer borehole shear test carried out at 3 m depth in a mid-consistency plastic clay. After discarding the 3 first points of the curve which are not representative, and fitting the linear Coulomb envelope $\tau(p_c)$ on the rest of the measured points, an in situ friction angle of $\varphi_i = 7°$ and a cohesion of c_i = 63 kPa are obtained.

The low value of the friction angle and the high value of cohesion are typical for this type of plastic clay in a short term and undrained behaviour. The injected volume curve and the creep expansion curve exhibit a relatively high variation, corresponding to a rather soft clay.

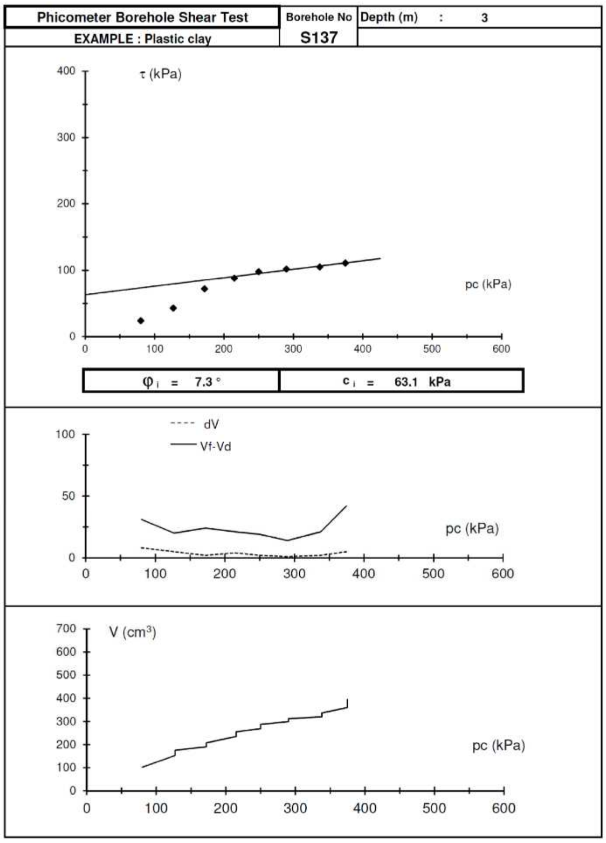

Figure 6. Example of a PBST test results in a plastic clay.

The Figure 7 shows the results obtained from a phicometer borehole shear test carried out at 3 m depth in a gravelly clay with cobbles. This kind of material with coarse particles cannot usually be tested with classic laboratory shear tests, like triaxial or direct shear tests, due to the limitation of allowable particle size.

The fitted linear Coulomb envelope $\tau(p_c)$ on the representative measured points, lead to an in situ friction angle of $\varphi_i = 17°$ and a cohesion value of c_i = 79 kPa.

The relatively low value of the friction angle and the high value of cohesion are typical for this heterogeneous gravelly clay in a short term and undrained behaviour. The injected volume curve and the creep expansion curve exhibit a high variation, corresponding to a rather low compactness material.

3.2. Test results obtained in particular materials

The feasibility of laboratory shear tests on coarse soils is made difficult by the high particle size of the elements composing these soils and by the difficulties of sampling and obtaining representative samples.

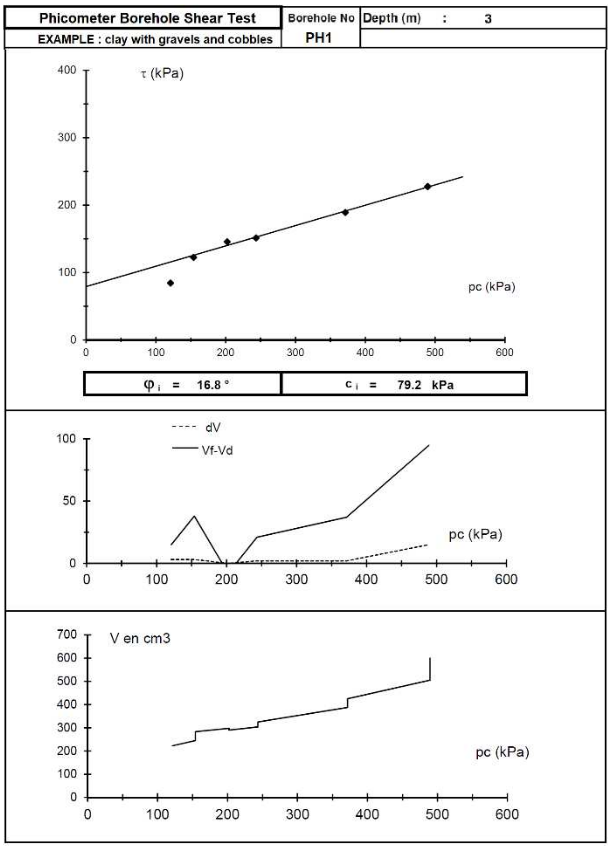

Figure 7. Example of a PBST test results in a gravelly clay.

Figures 8 and 9 reproduce the results of tests carried out on coarse sands and gravels in situ.

The test in Fig. 8 was carried out in a medium to coarse sandy gravel containing a grain size greater than 120 mm. The measured in-situ friction angle is $\varphi_i = 37°$ and cohesion is ($c_i = 0$ kPa). Given the high permeability and drainage capacity of this material, these values can be considered as effective characteristics.

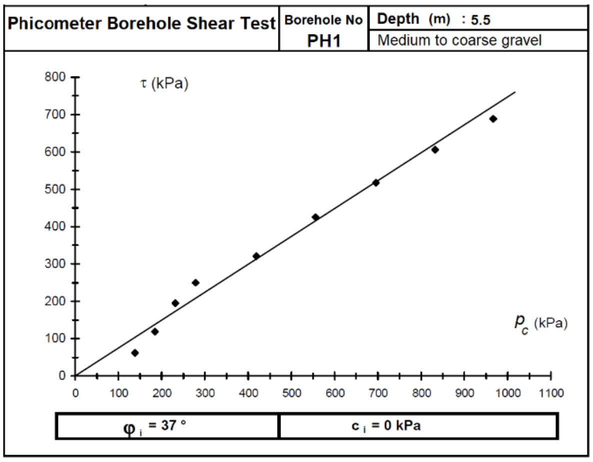

Figure 8. Example of a PBST test results in a medium to coarse gravel.

The result shown in Figure 9 corresponds to a test carried out at a quay wall of a harbour, subjected to scouring. It was conducted at a depth of 17.3 m in a medium to coarse gravel with cobbles and pebbles. In addition to the challenging drilling conditions (use of bentonite drilling fluid, combined with casing over the entire depth of the phicometer borehole), tidal fluctuations of the hydrostatic level had to be taken into account during drilling and for the analysis of the tests.

All the experimental measured points fit on the same linear Coulomb envelope. The linear adjustment on these points gives an in situ friction angle of $\varphi_i = 40°$ and no cohesion ($c_i = 0$ kPa) for this non-cohesive very coarse granular soil. The high value of the friction angle is consistent with the nature, density and in situ resistance of the tested soil.

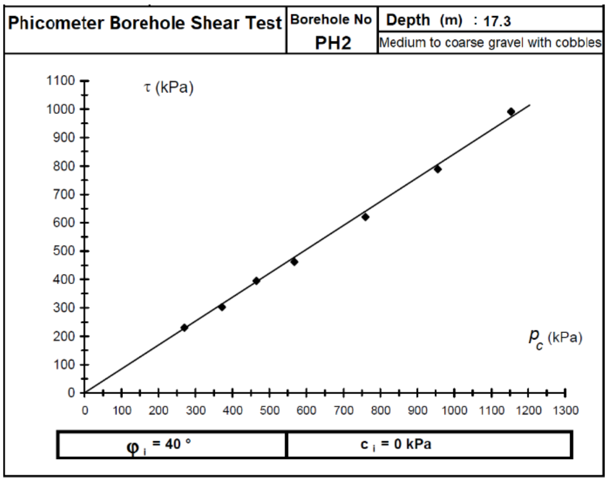

Figure 9. Example of a PBST test results in a medium to coarse gravel with cobbles.

3.3. Test results obtained in a municipal solid waste

More and more, there is a need to characterise the geomechanical behaviour of Municipal Solid Waste (MSW) in landfills. The knowledge of the shear resistance is necessary to study stability in landfill design and management. The MSW materials are very heterogeneous. Their composition can vary from one area to another and with time. Their particle size distribution includes either bulky and large size elements and small and very fine elements as well, which can influence their shear strength.

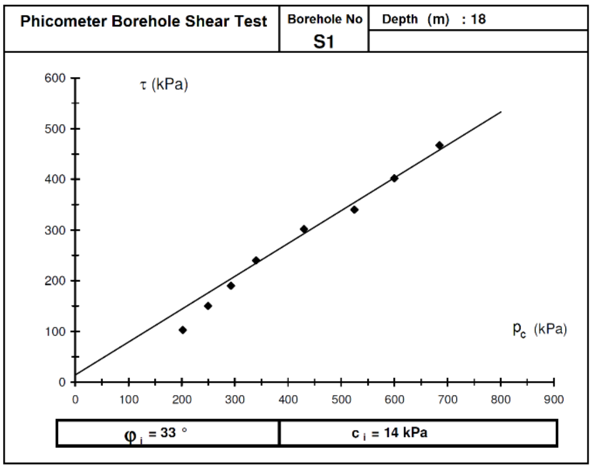

Figure 10. Example of a PBST test results obtained at 18m depth in a municipal waste MSW landfill.

Fig. 10 shows the results obtained from a PBST test in a MSW landfill, carried out at 18m depth. This waste material has been compacted following the landfill management rules.

Except the two first points of the diagram, the other experimental measured points follow the same linear adjustment giving thus an in situ cohesion of 14 kPa and an in situ friction angle of $\varphi_i = 33°$. These values correspond to a high shear strength material, mainly similar to an apparently granular and cohesive soil behaviour. However these values can only be an example and cannot be generalized given the significant amplitude of variation of these characteristics from one point to another in a same landfill and from one landfill to another.

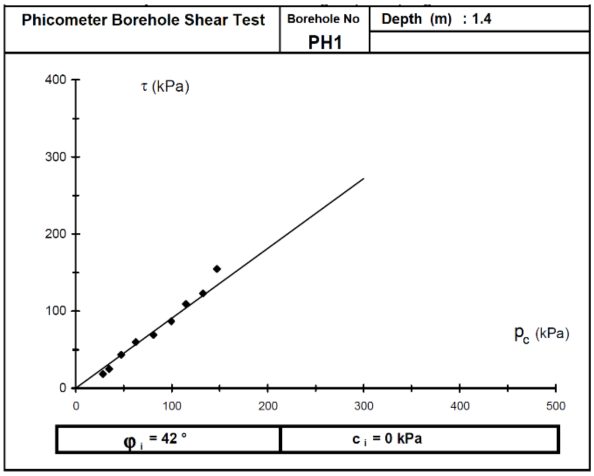

Figure 11. Example of a PBST test results obtained at 18m depth in a municipal waste MSW landfill.

The Incineration of Municipal Waste generates ash and clinker. Depending on the corresponding regulations, some categories of MSW incineration clinker can be reused in some construction works, like filling material under certain conditions. The knowledge of its geomechanical properties becomes then interesting.

Figure 11 shows a typical result of a borehole shear test carried out in a stockpile of incineration clinker, at 1.4m depth. This ash/clinker material maturation was approximately one year old. Most of the experimental points lie on a same linear adjustment giving an in situ friction angle of $\varphi_i = 42°$ and no cohesion, showing a behaviour similar to a coarse granular non- cohesive material one.

4. Deriving effective characteristics from PBST

The Phicometer borehole shear test in situ measured characteristics are "short term" type characteristics giving thus a direct measurement of typically undrained properties.

Depending on the nature and the permeability of the materials, the effective characteristics *c'* and *φ'* can be estimated through correlations published by Philipponnat and Zerhouni (Philipponnat and Zerhouni 1993). These correlations have been established for soils from comparisons of the PBST results with results obtained by laboratory shearing tests on the same materials. These correlations are given in table 1 for different soils.

Table 1. Correlations to estimate effective shear strength characteristics form the PBST results

φ_i (°)	c_i (kPa)	Type of soil	estimated φ' (°)	estimated c' (kPa)
≤ 15	< 20	Soft to very soft clay **	17	0
≤ 15	≥ 20	Medium to hard clay	17	c_i / 4
> 15 and ≤ 30	< 20	Other loose soils	φ_i *	0
> 15 and ≤ 30	≥ 20	Silts, clay-sand composites, clayey marls	φ_i *	c_i / 3
> 30	< 10	Granular soils	φ_i	0
> 30	≥ 10	Cohesive and granular soils except soft rocks	φ_i	c_i / 2
> 25	_	Soft rocks **	φ_i	> c_i

* or $\varphi' = 25°$ if $\varphi_i < 25°$ - ** not normally applicable in this type of soil

5. Conclusions

The determination of the shear strength of soils is of primary importance in geotechnical investigation and testing of soils. The shear resistance of soils and materials, characterized by the friction angle φ and the cohesion c, can be measured in situ with the phicometer borehole shear test (PBST). This test which provides a rapid in-situ mean for determining the shear resistance (cohesion and friction angle), is now covered by the international standard EN ISO 22476-16: 2024 that has been developed under the aegis of the ISO TC182 technical committee for Geotechnical investigation and testing.

Through a selection of some Phicometer in situ shear test results, it is possible to characterise the shear strength of grounds and particular materials, that are usually difficult to test in the laboratory, like coarse soils, heterogeneous soils, municipal solid waste, ash and clinker resulting from MSW incineration and many other materials in which intact sampling is difficult to achieve.

The Phicometer borehole shear test in situ measures "short term" type characteristics. The effective characteristics *c'* and *φ'* can be estimated through correlations given in table 1. These correlations have been established for a certain number of soils from comparisons with laboratory shearing tests.

The Phicometer Borehole Shear Test completes the list of tests allowing a direct determination of soil shear strength, available in the new generation of Eurocode 7 for geotechnical design – pr EN 1997 Part 2: Ground properties, to be published in 2027.

Acknowledgements

The authors would like to thank the members of the ISO/TC 182/WG 8 working group and the external experts who contributed to the development of

EN ISO 22476-16 standard, in particular the company APAGEO for the demonstration of a phicometric test on its site and the Luxembourg Institute for Standardisation (ILNAS), which supported this project from the very beginning.

References

EN ISO 22476-16 2024 "Geotechnical investigation and testing — Field testing — Part 16: Borehole shear test", ISO standard, www.iso.org, 2024

Philipponnat, G. 1986. "Le phicomètre: Essai de cisaillement direct in situ", Revue Française de Géotechnique, (35), 1986.

Philipponnat G., Zerhouni M. I. 1993 "Interprétation de l'essai au phicomètre", Revue Française de Geotechnique, (65), October, pp. 3-28, 1993