

Physical consistency: a useful tool for sludge characterization to the implementation of European standards

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The physical consistency, linked to the rheological and other mechanical properties, is a characteristic parameter of fundamental importance in characterization of both sewage and waterwork sludges, as it strongly affects almost all treatment, utilization and disposal operations, such as storage, pumping, transportation, handling, land-spreading, dewatering, drying, landfilling. In fact, the selection of the most suitable equipment and procedure for land application, storage and transportation of sludge, is strongly connected to its consistency. Similarly, compacting sludge in a landfill or forming a pile in composting is depending on sludge shear strength rather than on its solids concentration (Spinosa and Lotito, 1999).

In addition, references to the physical consistency are often reported in European legislation on sludge as a characteristic to be evaluated for fulfilling the regulations requirements.

In particular, according to the Sludge Directive 278/86, agricultural reused sludge must have agronomic interest, be healthy and easily usable, *i.e.* easily stored, transported, handled, and spread.

In Council Directive 1999/31/EC (Landfill Directive), Article 2 (q) gives a definition of “liquid waste”, and Article 5 (3.a) does not allow a liquid waste to be landfilled, but a standardized method for this evaluation has to be developed yet. Further, Annex II (2. General principles) requires that “The composition and general properties of a

waste to be landfilled must be known as precisely as possible”, and Annex I (6. Stability) is referring to “... ensure stability of the mass of waste ... particularly in respect of avoidance of slippage”, so the shear strength and piling behaviour must be known. Article 2 (h) says, that “treatment means ... processes ... in order to ... facilitate its handling”. Finally, Article 11 (1.b) asks for : “ – visual inspection of the waste at the entrance and at the point of deposit and, as appropriate, verification of conformity with the description provided in the document submitted by the holder”, so simple and easy tests to be carried out on the field and followed by the operators must be defined.

Further, the Council Directive of 16/12/02 “establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 and Annex II of Directive 1999/31/CE on the landfill of waste” included “consistency” among the basic parameters to be evaluated for waste characterization before landfilling. For specific cases it is also demanded that EU Member States must set criteria to ensure a sufficient physical stability and bearing capacity of waste.

Moreover, in many analytical methods for sludge characterization (e.g. pH, dry matter, leachability, etc.) different procedures are indicated depending on whether the sample to be examined is liquid or not, is solid or not, but no procedures are given for evaluating such properties. For this reason, the Technical Committee 308 of the European Committee for Standardization (CEN/TC308),

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established in 1993 for the development of standardized procedures for sludge characterization and use, included the “physical consistency” in its work programme (Leschber and Spinoso, 1998).

CEN/TC308 also promoted, with the contribution of the EU DG/Environment and the JRC, the development of a standardization “Horizontal” project aiming at the development of horizontal and harmonised European standards in the fields of sludge, soil and treated biowaste, to facilitate regulation of these major streams in the multiple decisions related to different uses and disposal governed by EU Directives. This is particularly important for the application of the mentioned Council Directive of 16/12/02, and in view of the revision of the Sewage Sludge Directive and the issuing of a Biowaste Directive which call for standards on sampling, on hygienic and biological parameters, on methods for inorganic and organic contaminants and for mechanical properties of these materials.

A part of the project will focus on “pre-normative” research required to develop standards lacking at this point and needed in the next revision of the regulations in these fields. This part includes the “flowability” (limit of liquid/paste-like consistency), “solidity” (limit of solid/paste-like consistency, shear-strength), “thixotropic behaviour” (limit of thixotrophy), and “piling behaviour” (limit of slippage, compaction behaviour) among the characteristics to be considered.

Background

The influence of sludge management operations on rheological properties has been studied by several authors.

With reference to the influence of sludge treatments, experiments conducted by varying the food to microorganism (F/M) ratio, and the carbon to nitrogen (C/N) one resulted in sewage sludges with remarkable differences in rheological characteristics not found for other generally used parameters, such as solids concentration, sludge volume index, etc. (Dick and Ewing, 1967). Furthermore, Dick (1965) found that during thickening the extent of deviation from the prevailing theoretical design procedures, such as that based on the solid flux, is correlable/correlated to the magnitude of the yield stress, while Geinopolos and Katz (1964) found a relationship between the capacity of the collector for a dissolved air flotation unit and the rheology of the sewage sludge being collected.

In chemical conditioning by polymers it was evidenced that municipal sludges develop a peak in the rheogram at the optimal dosage, thus allowing the automatic control of the conditioning process to be performed (Campbell and Crescuolo, 1989). The application of sludge rheology to process design and equipment selection for many unit operations, such as clarifying, thickening and dewatering, has been discussed by Martin (1999). At recent IWA specialist Conference on sludge in Moncton, a correlation between rheological parameters and full scale dewatering results was determined (Klinksieg *et al.*, 2007)

Regarding utilization/disposal operations, sludge can be applied to land in different ways depending on its physical state (U.S.EPA, 1979 ; 1984). In all cases, the selection of the best equipment to be used and optimal procedure adopted is strongly dependant on the consistency of the material, so the evaluation of rheological properties is essential. Sludge disposal in landfills (if allowed by national regulations) is commonly related to its solids concentration (~ 30-35 %), but this is not sufficient in many cases because the corresponding bearing capacity measured in terms of vane shear strength is not high enough. A reduction of apparent viscosity with storing time was also measured, in spite of the solids content which instead increased (Koehlhoff, 1990). It results that a vane shear strength of 10 kPa is at least necessary, but in Germany a minimum vane shear strength of 25 kPa is required for sludge landfilling (Wichmann and Riehl, 1997).

Finally, an effective optimization of sludge management requires the correct planning of the storage and transportation operations which enable the equalization between a continuous entering flow (production) and a discontinuous outlet one (use/disposal) and the utilization at sites far from those of origin.

Liquid sludge can be stored in tanks/vessels and excavated lagoons/ponds, and plastic/solid sludge in dumps, basins and containers. Sludge transportation can be performed by pipeline, barge, rail or truck. Again, the selection of the most suitable system and equipment of storage and transportation depends basically on the sludge physical consistency, so the knowledge of the physical characteristics is an essential condition for choosing the installation, designing it and operating the whole system.

Physical states

The assessment of physical and mechanical characterization methods and tests firstly requires the definition of the different physical state of sludge.

The following three consistency categories have been proposed for sludge (CEN, 2007) :

- *Liquid* : sludge flowing under the effect of gravity or pressure below a certain threshold ;
- *Paste-like* : sludge capable of continuous flow under the effect of pressure above a certain threshold and having a shear resistance below a certain threshold ;
- *Solid* : sludge having a shear resistance above a certain threshold.

This firstly involves the necessity to set up methods to measure values in the range of the boundary area between liquid and paste-like behaviours (limit of *flowability*) and that between solid and paste-like (limit of *solidity*).

As told, both above parameters, flowability and solidity, are of fundamental importance in many sludge management operations, such as pumping, transportation, storage, dewatering, stabilization, spreading, etc., so the usefulness of rheological and other mechanical measurements in sludge management in relation to treatments (biological, physical-chemical), utilization/disposal (agricultural use, landfilling), and handling (pumping, storage, transportation) has been extensively discussed in CEN/TC308.

Table 1 shows the applicability of different treatment/disposal options on sludge having different physical state.

▼ Table 1 – Importance of the sludge physical states in its management (L = Low ; M = Medium ; H = High).

Operation	Liquid	Paste-like	Solid
Stabilization	H	M	L
Dewatering	H	M/L	L
Storage/ Transportation	H	H	H
Agricultural use	H	H	H
Landfilling	L	M/H	H
Incineration	L	M/H	H

Further, the *thixotropic behaviour* of solid materials (from “the solid to the liquid state and vice-versa”) should be evaluated, together with the *piling behaviour* ; the measurement of thixotropic behaviour is important for solid materials, e.g. dewatered sludge, that could get a liquid state during operations, such as transportation, due to the vibration of e.g. a truck, while the determination of the piling angle is a useful tool to characterize the storage properties and calculate the space, which is needed for e.g. storage and transportation.

Although methods to be developed are partly known and used in other technology fields, e.g. soil mechanics, materials for construction works (concrete, suspensions), etc., widely accepted methodologies for the evaluation of above properties, able to give comparable and reliable results, are not available yet. These methodologies should also be supplemented by simple to operate and applicable in-the-field testing methods.

It therefore follows the need to define simple and reliable measurement procedures to be applied in the field, together with those to be used as reference in laboratory. These aspects are discussed in the following.

Existing standards and methods

The first action carried out consisted in searching for existing standards and non-standardized methods to be possibly used or adapted for utilization in the specific field of consistency evaluation for sludge. To this purpose, documents of several standardization organizations, including ISO, ASTM, CEN, UNI, DIN, AFNOR, BSI, ASAE, etc., were examined (Battistoni *et al.*, 2003 ; Wichmann *et al.*, 2003).

Flowability

Flowability is the state in which a material is able to “flow”, *i.e.* it behaves as a liquid. This characteristic is, therefore, strictly connected to rheological properties, as rheology is the science of deformation studying the relationship between shear stress (internal stress) and shear rate (velocity of deformation) which can be depicted in a rheogram.

The rheological behaviour of very thin sludges is Newtonian, like water, where the viscosity is independent of the shear rate and no initial

resistance (yield stress) is shown if a force is applied at rest :

$$T = \mu D$$

where T is the shear stress, D the shear rate and μ the viscosity.

Instead, the behaviour of more concentrated suspensions is described as non-Newtonian : they may exhibit a yield stress and the viscosity may vary with the shear rate : a general equation is :

$$T = T_0 + \mu D^n$$

where T_0 is the yield stress, μ the plastic viscosity or fluid consistency index, and n the fluid behaviour index.

In the Bingham plastic model $n = 1$, so no curvature of the rheogram is exhibited ; this model should seem to be preferable, as it allows to define a unique viscosity-type coefficient, plastic viscosity, measured by the slope of the line of shear stress vs. shear rate (Battistoni *et al.*, 1991 ; 1993).

A lot of viscometers are available to evaluate this property (Table 2). They generally fall into two general categories : tube type (often referred to as capillary viscometer), and rotating type.

The use of a tube viscometer is a good approach, but the tube diameter must be large enough to prevent any clogging phenomenon, which means that the tube has to be quite long in order to obtain measurable head losses.

Rotational viscometers are generally considered to be more useful. They may have (i) coaxial cylinders with moving inner or outer cylinder, (ii) rotating blades and (iii) cone-plate geometry. The drawback of coaxial cylinder types is that cylinders have to be very close together when studying low concentrated and/or not very viscous sludge. Consequently, there is a risk of obstruction by grains of sand, fibers and other solid materials. Other drawbacks are the separation of particles due to the gravitational and centrifugal fields and the phenomenon of slip occurring at the cylinder/liquid interface, which can be overcome by artificially increasing the roughness of the moving cylinder.

In the case of viscometers with blades, or vane apparatus, the velocity gradient is less well defined, so only a mean value based on the mechanical energy dissipated in the medium, calculated from measuring the drive torque of the mover, can be obtained.

The cone-plate geometry rheometers can be excluded on the basis of both the large size of sludge particles relative to the gap and the poor liquid sludge consistency.

Solidity

Solidity is the state in which a substance has no tendency to flow under moderate stress, resists forces (such as compression) that tend to deform it, and retains a definite size and shape.

For determination of solidity, besides the resistance to pressure, the flexural resistance and tensile strength, the "undrained shear strength c_u " is an important parameter. Shear may be defined as the tendency of one part of e.g. a soil mass to slide with respect to the other. This tendency occurs on all planes throughout the soil mass. The singular plane of interest, however, is the plane of potential failure, called the plane of rupture. Shear strength, as measured along this plane of interest, is the ability of the mass to resist the occurrence of a shear failure between the soil above and below the plane. Solid bodies, e.g. soils, have the ability to develop strength in shear. Different material groups develop this strength in different ways.

Generally the cohesion c , as defined in geotechnical science, has to be determined on basis of the evaluation of the shear strength τ as a function of the applied axial strength σ using the Coulomb rule :

$$\tau = c + \sigma \cdot \tan \varphi$$

where φ is the angle of shearing resistance or friction angle. For sludges, it has been observed that φ is near zero (Costet and Sanglerat, 1975). For this reason it is reasonable to consider equal τ and c ; furthermore, several authors (Gazbar, 1993 ; Abadie and Tisot, 1997) considered that the yield stress (the stress above which the sludge is deformed) is equal to τ , so it is proposed that $\tau_r = c_u$ where c_u is the undrained cohesion or the undrained shear strength.

The ability of a mass to support vertical loads and to resist the sliding effect of lateral loads, is governed to a large extent by the shear strength of the material. There are several field and laboratory tests by which shear strength can be determined with reasonable accuracy : they are Triaxial compression tests, Vane shear tests or Direct shear tests.

Thixotropic and Piling behaviours

Waterworks and sewage sludge often exhibit a thixotropic behaviour: during shear stress the sludge changes from the solid to the liquid state. This may hinder the utilization of the sludge during transport and handling, so it must be ensured that dewatered sludge is not fluidized during transport and handling. Therefore it must be measured whether the material is behaving thixotropic and, if so, under which conditions.

Sludges usually have to be stored during transportation or storage in e.g. piles or containers. To avoid problems with succeeding handling operations the pieces of these materials should undergo no major changes in form and consistency. From there it is of great importance to investigate the piling behaviour, which is displayed by the materials.

The "compactibility" is a first supporting parameter for determination of the piling behaviour. This parameter could give information about how much a stratum of piled material can settle due to the loading of the material placed above. The measurement of the "piling angle (angle of rest)" or "slope angle" is also a very helpful parameter to determinate the piling behaviour (Pasqualini *et al.*, 2003). The instrument for measuring these parameters consists of a simple box with turnable sidewalls.

On the basis of the selected list of standards and non-standardized methods for further consideration, the methods for the determination of flowability, solidity, thixotropic behaviour and piling behaviour of sludge have been divided into several groups, according to the instruments used for measuring.

The following devices have been considered:

– for flowability: *capillary viscometer, penetrometer, rotational viscometer, and flow apparatus devices*;

– for solidity: *shearing apparatus, vane testing apparatus, and penetrometer*;

– for piling behaviour: *slump test apparatus, compacting apparatus (e.g. Oedometer), CPB-cubic piling box, and turned box.*

For the determination of the *thixotropic behaviour* of solid materials, a standard method does not exist. From there it should be investigated a combination of methods for determination of the solidity, like penetration, etc., and an energy-input in terms of "flow" apparatus to simulate the shear stress.

Recommended methods

Methods selected for evaluation of flowability are listed in the following Table 2 (Battistoni *et al.*, 2003) and shown in Figures 1 and 2, together with indication about their possible applicability as laboratory test or field one.

Table 3 gives an overview of the recommended apparatuses and methods for determination of the solidity (Figures 3 and 4), thixotropic behaviour (Figures 5 and 6), and piling behaviour (Figure 7) (Wichmann *et al.*, 2003).

▼ Table 2 – Summary of the recommended apparatuses for flowability.

Method/Apparatus	Employment
Shear controlled coaxial cylinders viscometer	Laboratory test
Flow cone	Field test
Penetration cone for yield stress measurement	Field test
Extrusion tube viscometer (Kasumeter)	Field test
Inclined plane	Field test
Modified slump test	Field test

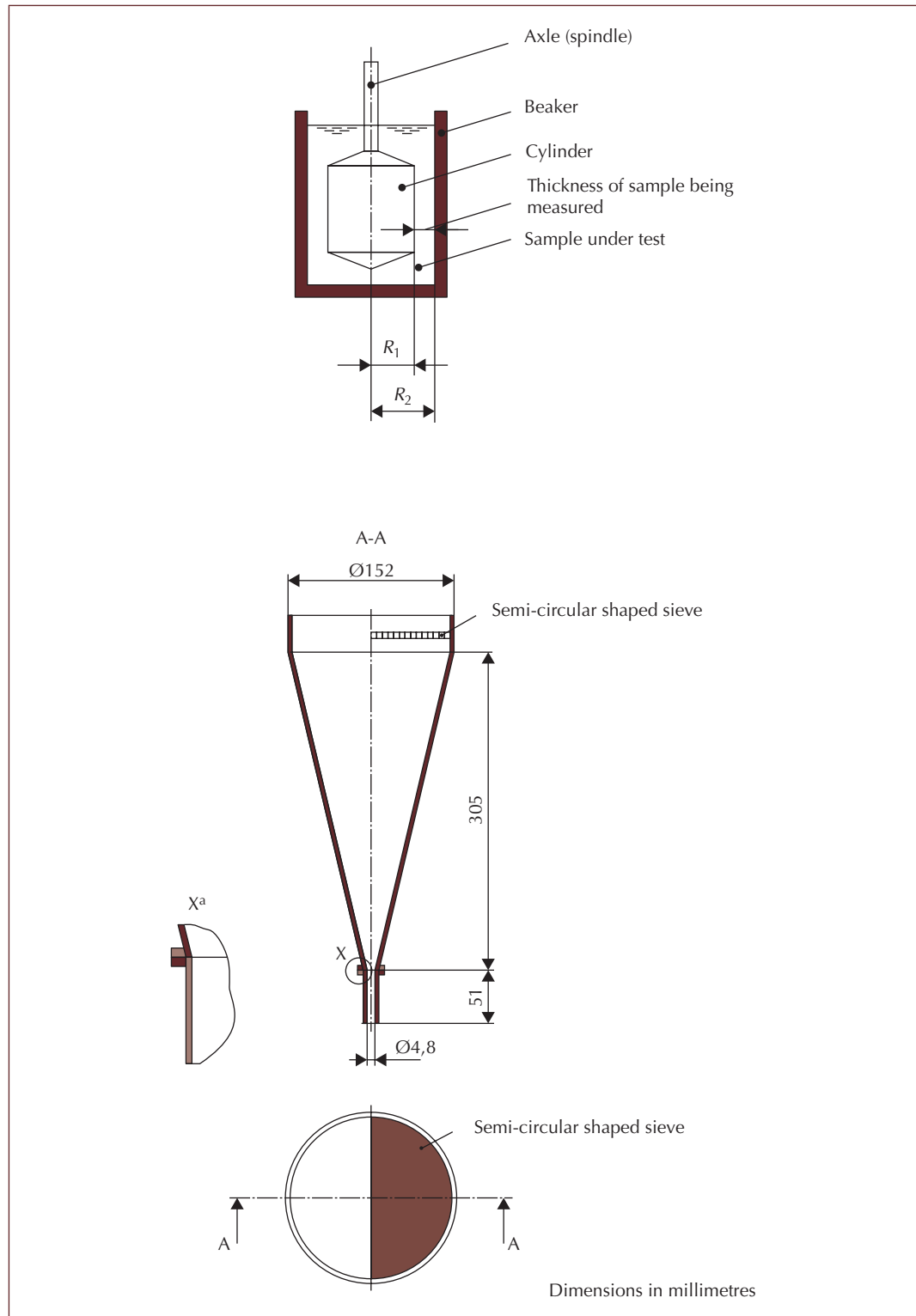
▼ Table 3 – Summary of the recommended apparatuses for solidity, thixotropic behaviour and piling behaviour.

Method/Apparatus	Solidity	Thixotropic behaviour	Piling behaviour
Penetrometer	Shear strength (Lab / Field)	Shear strength (Lab*/Field+/**)	
Vicat needle apparatus	Shear strength (Lab)		
Laboratory vane shear apparatus	Vane shear strength (Lab)		
Pocket penetrometer (Neuschäfer)	Bearing capacity ¹ (Field)		
Pocket cylinder penetrometer	Unconfined compression strength ² (Field)		
Vibrating table		Shear strength (Lab*/Field ⁺)	
Hammer (manual)		Shear strength (Field ^{**})	
Cubic piling box (CPB)			Piling angle (Lab/Field)
Oedometer			Compactibility (Lab)

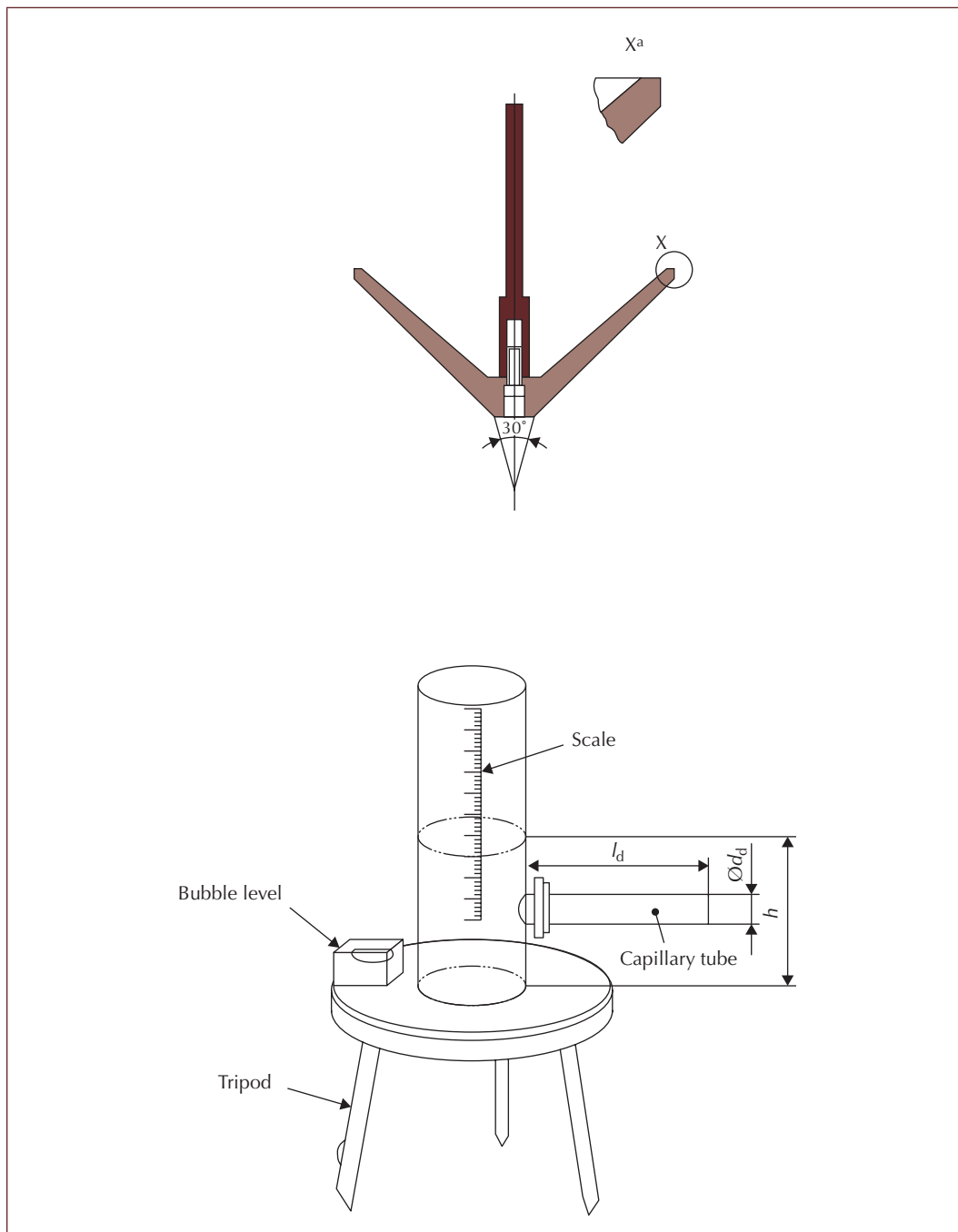
Notes: – Combinations for thixotropic behaviour: ***, **+, **+, **+, **+

1. Conversion into shear strength possible

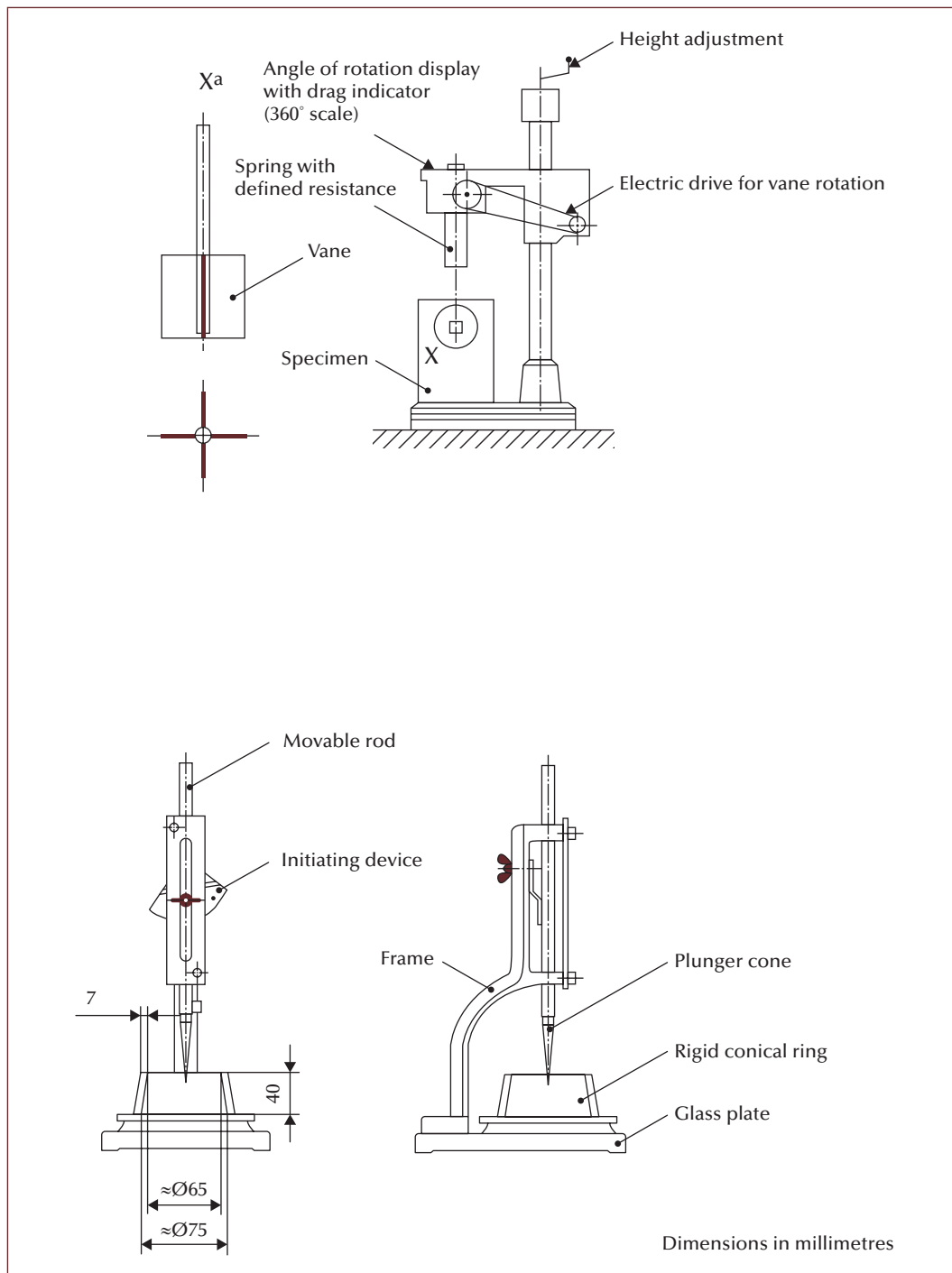
2. Conversion into undrained shear strength possible



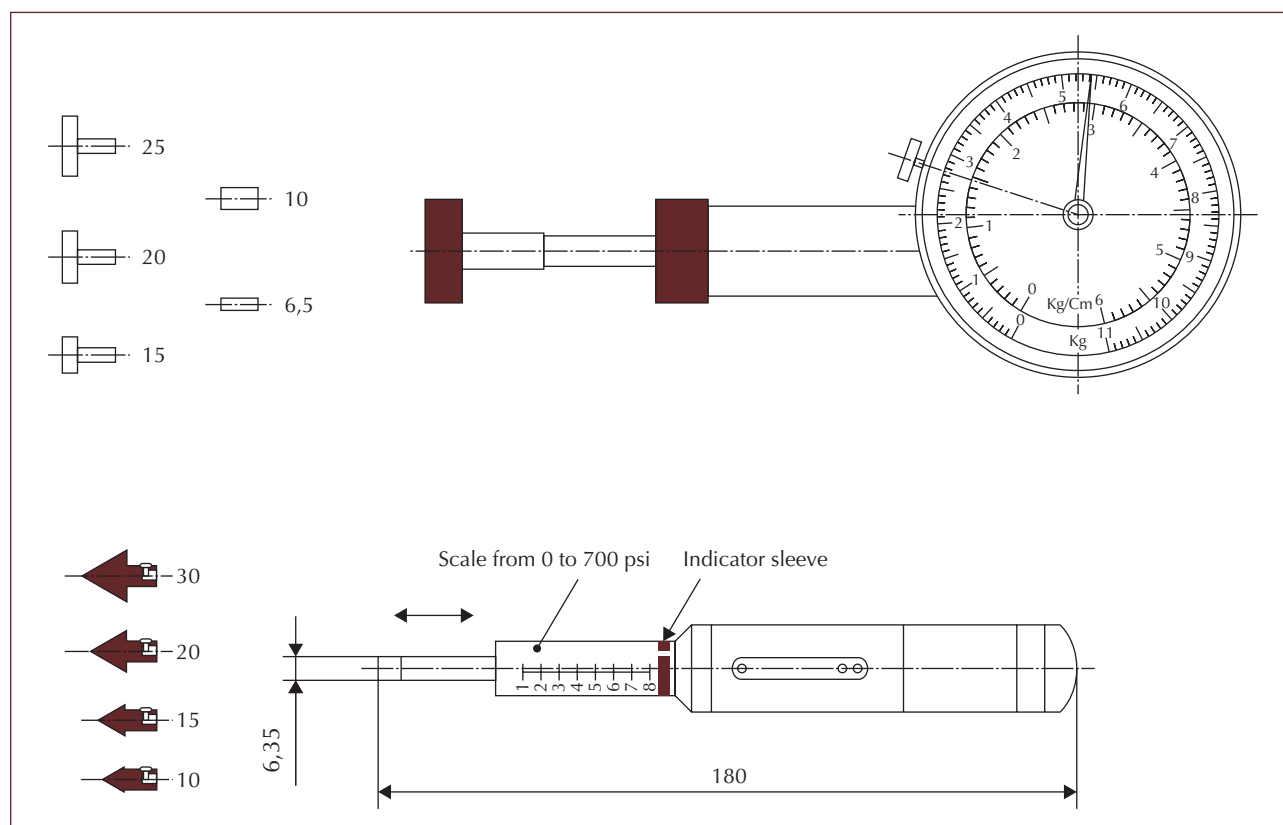
▲ Figure 1 – Methods for evaluation of flowability (Coaxial cylinder viscometer) (Flow cone).



▲ Figure 2 – Methods for evaluation of flowability (Magnesium penetration cone) (Tube extrusion viscometer – Kasometer).



▲ Figure 3 – Methods for evaluation of solidity (Lab vane shear apparatus) (Vicat apparatus).



▲ Figure 4 – Methods for evaluation of solidity (Pocket cylinder penetrometer) (Pocket penetrometer after Neuschäfer).

Conclusions

The physical consistency is a characteristic parameter of fundamental importance in characterization of both sewage and waterwork sludges, as it strongly affects almost all treatment, utilization and disposal operations, such as storage, pumping, transportation, handling, land-spreading, dewatering, drying, landfilling.

In addition, references to the physical consistency are often reported in European legislation on sludge as a characteristic to be evaluated for fulfilling the regulations requirements.

From the analysis of methods found in literature to be possibly applied for evaluation of sludge consistency, it appears that the recommended methods for determination of :

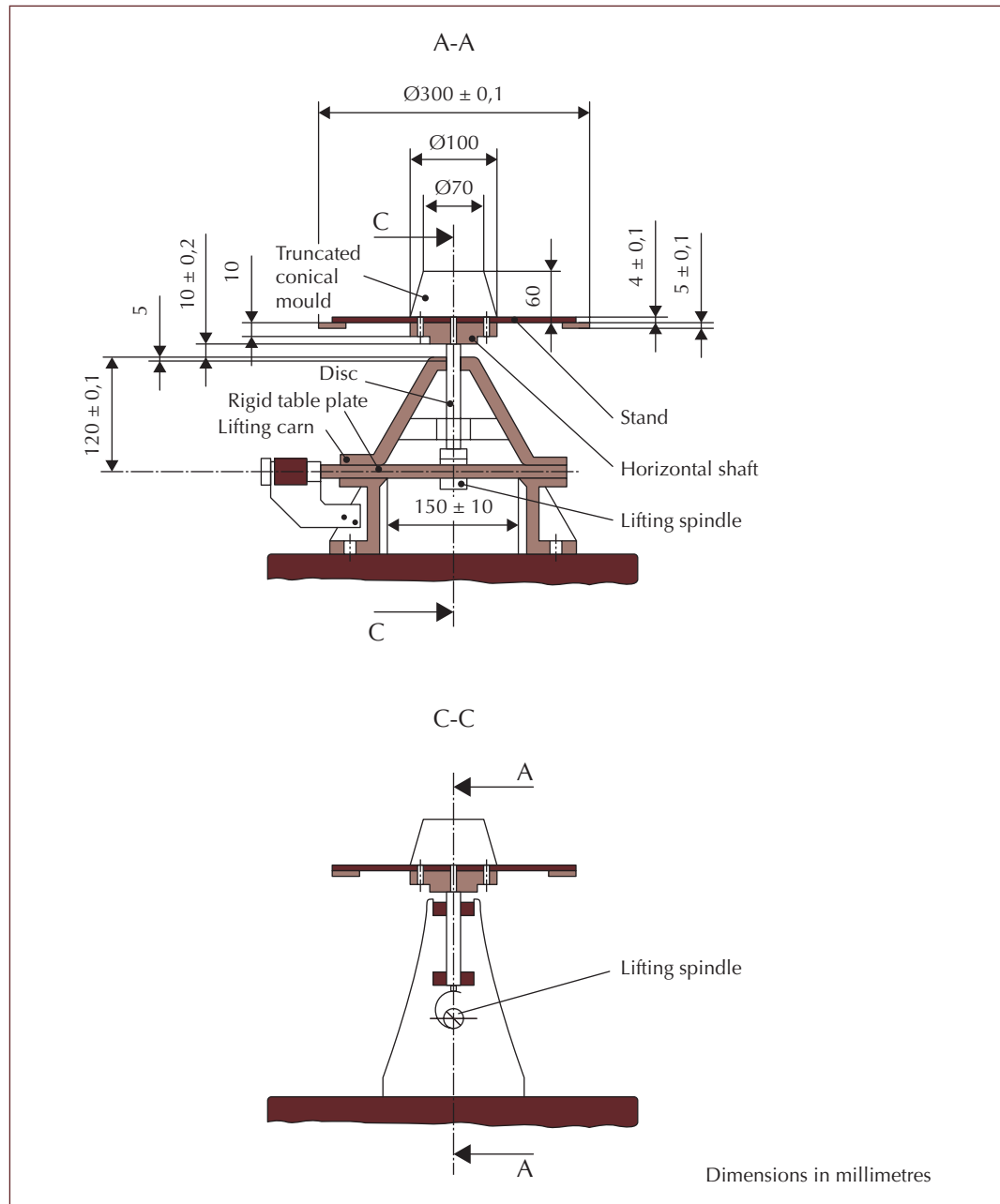
– *flowability* are the Coaxial cylinder viscometer, as laboratory apparatus, and the Flow cone, the Magnesium penetration cone, and the Extrusion tube viscometer as field apparatuses (Figures 1 and 2) (CEN, 2007) ;

– *solidity* are the Laboratory vane shear and the Vicat needle apparatuses, as laboratory reference method, and the Pocket penetrometer for field test, the latter being possibly used for both laboratory reference method and field test (Figures 3 and 4) (CEN, 2007).

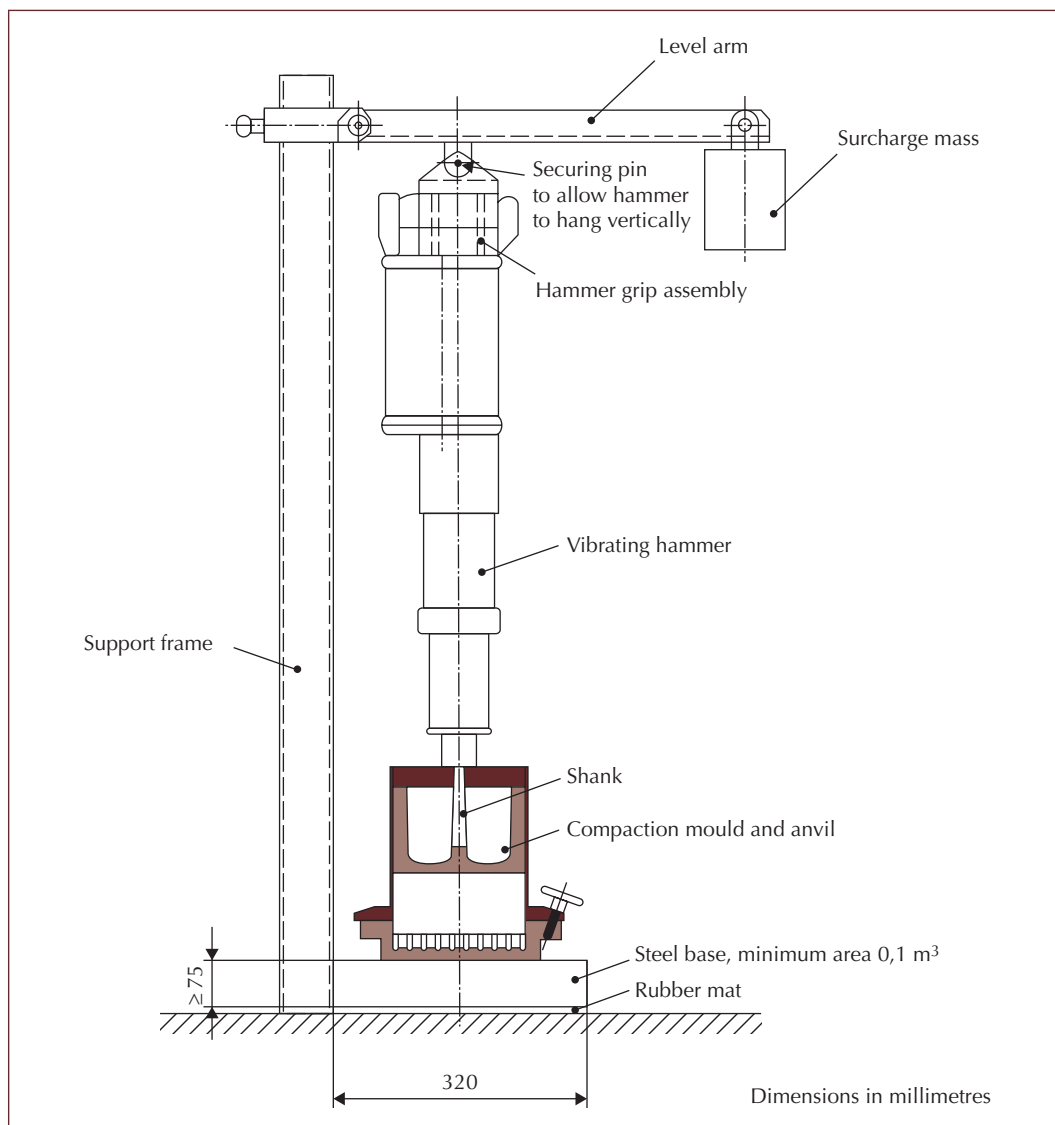
For determination of the *thixotropic behaviour* the penetrometer coupled to an energy-input, such as a vibrating table or a hammer, appears to be a suitable instrument (Figures 5 and 6) (CEN, 2007).

As far as the evaluation of the *piling behaviour* is concerned, the Cubic Piling Box (CPB) and the Oedometer appear to be the recommended methods (Figure 7) (CEN, 2007).

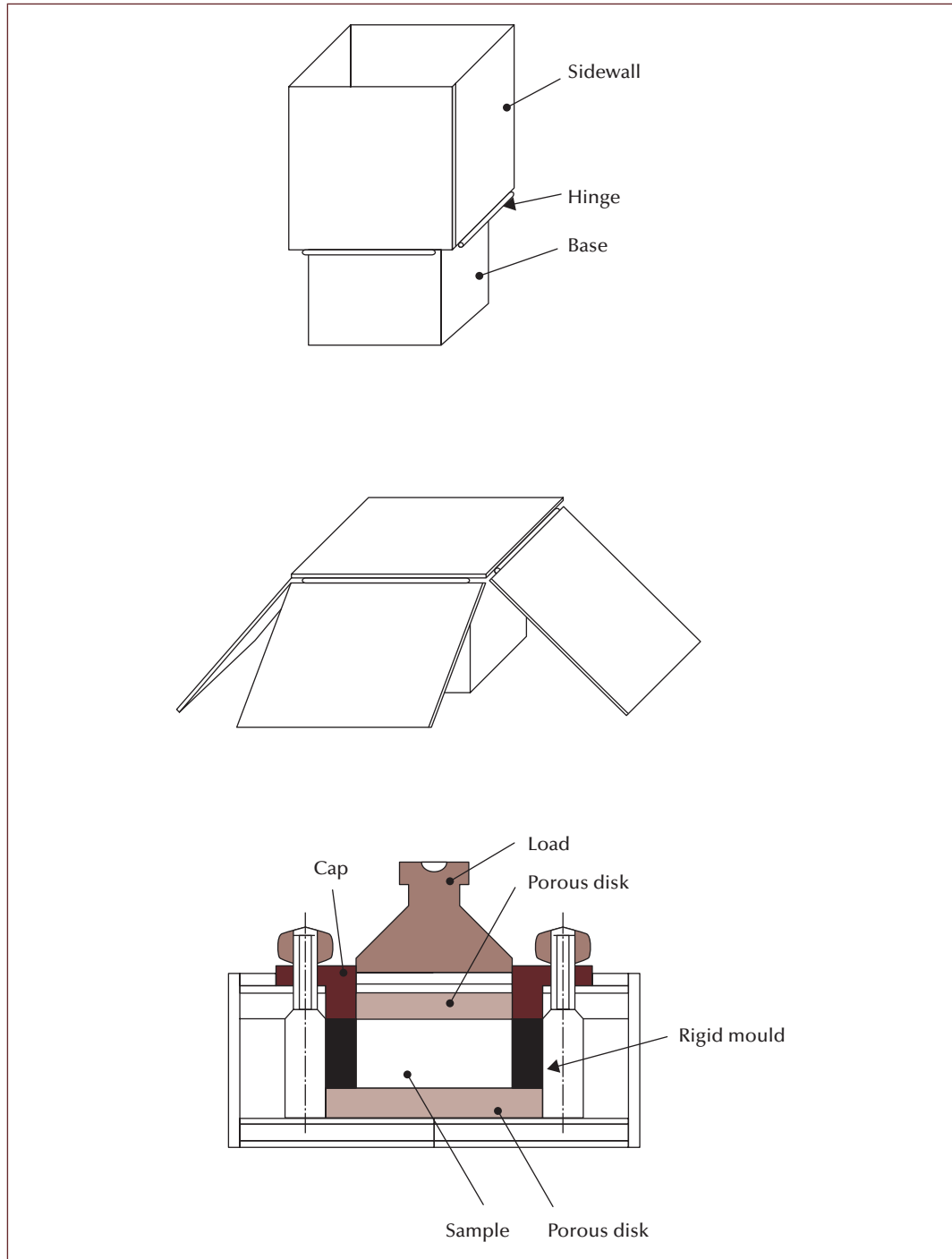
Future planned work will consist in optimizing and properly designing above devices in view of the development of standard methodologies. □



▲ Figure 5 – Methods for evaluation of thixotropic behaviour (Vibrating table).



▲ Figure 6 – Methods for evaluation of thixotropic behaviour (Compaction rig assembly with vibrating hammer).



▲ Figure 7 – Methods for evaluation of piling behaviour (Cubic piling box at test start) (Cubic piling box at test end) (Oedometer).

Abstract

Physical consistency is an important property for sludge characterization, as it affects almost all treatment, utilization and disposal operations. Three physical states have been evidenced for sludge : liquid, paste-like, and solid, whose boundaries are defined by limits of “flowability” and “solidity”. Characterization is completed by the evaluation of thixotropic and piling behaviours. In this paper, the work carried out by CEN/TC308 in this field is discussed. For evaluation of flowability, Coaxial cylinder viscometer, Flow cone, Magnesium penetration cone and Extrusion tube viscometer appear the recommended methods, and for that of solidity, Laboratory vane shear, Vicat needle, and Pocket penetrometer. The Penetrometer, coupled to an energy-input system, appears suitable for thixotropic behaviour evaluation, while the Cubic Piling Box (CPB) and the Oedometer for piling behaviour one.

Résumé

La consistance physique est une propriété importante pour la caractérisation des boues car elle a une influence sur toute opération de traitement, de valorisation et de stockage. On distingue trois états physiques pour la boue : liquide, pâteux et solide, dont les frontières sont définies par des limites de comportement à l'écoulement et à la solidification. La caractérisation est complétée par une évaluation de son comportement thixotrope et au tassement. Dans cet article, les travaux réalisés par le CEN/TC 308 dans ce domaine sont abordés. Pour l'évaluation de l'aptitude à l'écoulement, le viscosimètre à cylindres coaxiaux, le cône d'écoulement, la pénétration à cône de magnésium et le viscosimètre à tube d'extrusion sont les méthodes recommandées, et pour l'aptitude à la solidification, ce sont les appareillages à cisaillement de palette, de Vicat, et le pénétromètre de poche. Le pénétromètre couplé à un système d'apport d'énergie, convient pour l'évaluation du comportement thixotrope alors que le CBP et l'oedomètre sont utilisés pour l'évaluation du comportement au tassement.

Bibliographie

- ABADIE, J.-M., TISOT, J.-P., 1997, Geomechanical approach to the study of residual sludge, *in : The rheology of sludges*, International Workshop Association on Water Quality, CNR-Water Research Institute, Bari (I), March 17, p. 73-83.
- BATTISTONI, P. *et al.*, 1991, Rheology of sludge from semi-dry anaerobic digestion of municipal solid waste, *Environmental Technology*, n° 12, p. 897-905.
- BATTISTONI, P. *et al.*, 1993, Feed characteristics and digester operative conditions as parameters affecting the rheology of digested municipal solid wastes, *Water Science and Technology*, n° 27 (2), p. 37-45.
- BATTISTONI, P. *et al.*, 2003, Physical properties – Flowability, *Horizontal Report 21 (WP7-Part A)*, Polytechnic University of Marche Region, Ancona (I), (<http://www.ecn.nl/horizontal/downloads/finaldeskstudies/> or <http://www.eionet.eu.int>)
- CAMPBELL, H.-W., CRESCUOLO, P.-J., 1989, Control of polymer addition for sludge conditioning : a demonstration study, *Water Science and Technology*, n° 21 (10-11), p. 1309-1317.
- CEN (European Committee for Standardization), 2007, Characterization of sludge – Physical consistency – Thixotropic behaviour and piling behaviour, *Technical Report 15463*, Brussels, April, 84 p.
- COSTET, G., SANGLERAT, G., 1975, *Cours pratique de mécanique des sols (Tomes 1 et 2)*, 2^e édition, Dunod.

- DICK, R.-I., 1965, *Applicability of prevailing gravity thickening theories to activated sludge*, Ph.D. Thesis, University of Illinois, Urbana, (ILL-USA).
- DICK, R.-I., EWING, B.-B., 1967, The rheology of activated sludge, *J.W.P.C.F.*, n° 39 (4), p. 543-560.
- GAZBAR, S., 1993, *Évaluation et amélioration des performances des procédés de déshydratation mécanique des boues résiduelles*, thèse de doctorat de l'institut polytechnique de Lorraine.
- GEINOPOLOS, A. and KATZ, W.J., 1964, *A study of the rotating cylinder sludge collector in the dissolved air flotation process*, *J.W.P.C.F.*, n° 36 (6), p. 712-721.
- KLINKSIEG, K. *et al.*, 2007, Rheology and dewaterability of municipal sewage sludge, *in : Proc. IWA Conf. Wastewater Biosolids Sustainability : Technical, Managerial and Public Synergy*, Moncton (CAN), June 24-28, p. 149-155.
- KOEHLHOFF, D., 1990, Disposal of sewage sludge in landfills, *in : IAWPRC Sludge Mgt. Conference*, Loyola Marymount Univ., Los Angeles, January 8-12.
- LESCHBER, R., SPINOSA, L., 1998, Developments in sludge characterization in Europe, *Water Science and Technology*, n° 38 (2), p. 1-7.
- MARTIN, A.-D., 1999, Impact of sludge rheology on process design and equipment selection, *in : Workshop on sludge rheology and reuse*, Inst. for Env. Science, Murdoch Univ., Fremantle (W. Australia), April 7.
- PASQUALINI, E. *et al.*, 2003, Mechanical characterization of municipal solid waste (in Italian), *Proc. Annual Meeting of the Researchers in Geotechnics*, IARG.
- SPINOSA, L., LOTITO, V., 1999, Rheological measurements and their application in biosolids management, *Water21*, Sept-Oct, p. 28-29.
- U.S.EPA, 1979, *Process design manual for sludge treatment and disposal*, EPA 625/1-79-011, Cincinnati (OH-USA).
- U.S.EPA, 1984, *Use and disposal of municipal wastewater sludge*, EPA 625/10-84-003, Washington DC (USA).
- WICHMANN, K., RIEHL, A., 1997, Mechanical properties of waterwork sludges – e.g. shear strength, *Water Science and Technology*, n° 36 (11), p. 43-50.
- WICHMANN, K. *et al.*, 2003, Physical properties – Solidity, Thixotropic behaviour and Piling behaviour, *Horizontal Report 22 (WP7-Part B)*, Technical University Hamburg-Harburg (TUHH), Hamburg (D). (<http://www.ecn.nl/horizontal/downloads/finaldeskstudies> or <http://www.eionet.eu.int>)