Sludge characterization: the rôle of physical consistency

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Abstract The *physical consistency* is an important parameter in sewage sludge characterization as it strongly affects almost all treatment, utilization and disposal operations. In addition, in many European Directives a reference to the physical consistency is reported as a characteristic to be evaluated for fulfilling the regulations' requirements. Further, in many analytical methods for sludge, different procedures are indicated depending on whether a sample is liquid or not, is solid or not. Three physical behaviours (*liquid*, *paste-like* and *solid*) can be observed with sludges, so the development of analytical procedures to define the boundary limit between liquid and paste-like behaviours (*flowability*) and that between solid and paste-like ones (*solidity*) is of growing interest. Several devices can be used for evaluating the flowability and solidity properties, but often they are costly and difficult to be operated in the field. Tests have been carried out to evaluate the possibility to adopt a simple extrusion procedure for flowability measurements, and a Vicat needle for solidity ones.

Keywords Characterization; management; physical consistency; rheology; sewage sludge

Introduction

The physical consistency, which is a characteristic strictly linked to the rheological properties, is a parameter of fundamental importance in sewage sludge and waterworks sludge characterization, 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 depends 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 regulation 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.

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More recently, 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), established in 1993 for the development of standardized procedures for sludge characterization and use (Leschber and Spinosa, 1998), included the "physical consistency" in its work programme.

CEN/TC308 also promoted, with the contribution of the EU DG/Environment and the JRC, the development of a standardization "*Horizontal*" project, whose working budget is in the order of €1.5 M. This project is 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 (draft April 2000) and the issuing of a Biowaste Directive (2nd draft Working Document, Feb 2001) 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 "*co-normative*" work, with an emphasis on horizontal standardization starting from existing standards developed for the same parameter in the fields of sludge, soil and treated biowaste, while another part 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. The latter part included the "*flowability*" (limit of liquid/paste-like consistency), *solidity* (limit of solid/paste-like consistency, shear-strength), *thixotropic behaviour* (limit of thixotropy), 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 microorganisms and the carbon to nitrogen ratios resulted in 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 correlatable 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 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, 1983). 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).

Regarding utilization/disposal operations, sludge can be applied to land in different ways depending on its physical state (US EPA, 1979; 1984). In all cases the selection of the best equipment to be used and optimal procedure adopted is strongly dependent on the consistency of the material, so the evaluation of rheological properties is essential. Sludge disposal in sanitary landfills is commonly related to its solids concentration (~30–35%), but in many cases this is not sufficient 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 seems that a vane shear strength of 10 kPa is at least necessary.

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 exiting one (use/disposal) and the utilization at sites far from those of the 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 rheological characteristics is an essential condition for choosing the installation, designing it and operating the whole system.

Physical states and measurements

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/TC 308, 1995; Spinosa *et al.*, 1999):

liquid, sludge flowing under the effect of gravity or low pressure;

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 high shear resistance.

This involves the need to set up laboratory methodologies to define the boundary limit between liquid and paste-like behaviours (*flowability*) and that between solid and paste-like behaviours (*solidity*). Table 1 shows the “applicability” of different treatment/disposal options on sludges having different physical states.

Widely accepted methodologies for the evaluation of sludge consistency, able to give comparable and reliable results, are not available yet.

Viscometers, or rheometers, are the instruments commonly used for evaluating the consistency of liquid and paste-like sludges. Viscometers are of two types: tube, and rotating (coaxial cylinders, rotating blades and cone-plate geometry). When using a tube viscometer, only high flowable sludges can be tested and the tube diameter must be large enough to prevent any clogging phenomenon. The drawback of coaxial cylinder viscometers is that cylinders have to be very close together with low concentrated and/or not very viscous sludges; consequently, there is a risk of obstructions by grains of sand, fibres and other

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

solid materials. Another drawback is the slipping phenomenon occurring at the cylinder/liquid interface. In the case of viscometers with blades, or vane apparatus, only a mean value based on the mechanical energy dissipated in the medium, calculated by measuring the drive torque of the mover, can be obtained. The cone-plate geometry viscometers can be excluded on the basis of both the large size of sludge particles relative to the gap and the poor sewage sludge consistency.

For sludge in solid state, rotational rheometry appears less adapted than oscillatory measurements or compression tests, because the strength of a solid material depends on its ability to sustain a load without failure. Therefore, the best indication of this state could be obtained by measuring the deformation produced by a given stress through a penetrometer device.

However, the above mentioned rheological methods often require costly equipment and are quite complicated and difficult to be run in the field, so in addition to laboratory methods the development of simple, cheap and easy to operate in-the-field procedures, such as those based on the use of extrusion cells for flowable sludge (liquid) and portable penetrometers for non-flowable ones (paste-like/solid), are to be preferred.

Experimental work

According to Baudez (2003), it can be assumed that a liquid sludge has no yield stress, while a paste-like one does, so yield stress could be used to distinguish liquid and pasty states, while the solid state represents materials which cannot flow in steady state, so the behavior law links the shear stress to the shear strain, rather than the shear rate.

Flowability tests

As previously told, the yield stress is a typical characteristic of non-Newtonian fluids, and the non-Newtonian behaviour becomes evident at higher solids concentration, so the yield stress can be considered as indicator of sludge flowability.

For this purpose, a simple extrusion apparatus (Kasumeter) was used. It consists of a cylindrical acrylic container (Ø = 0.1 m; h = 0.35 m; $V \sim 0.003$ m^3) to which calibrated pipes of length 0.2 m and different diameters (Ø = 2.5, 5, 10, 16, 20 mm) can be fitted at the bottom. Yield stress values are measured from the time during which a continuous flow is occurring, and the corresponding height of the suspension remaining in the cylinder. At these conditions $\tau_0 = 3/8_* \rho ghr/l$, where τ_0 is the yield stress (Pa), ρ the suspension density (kg/m^3), g the gravity acceleration (m/s^2), h the height of the suspension remaining in the cylinder (m), r the tube radius (m), and l the tube length (m) (Schulze *et al.*, 1991).

Tests were run by Spinosa and Lotito (2001) using a municipal sewage sludge at different solids concentrations (obtained through dilution of dewatered sludge by means of filtrate), and two synthetic suspensions of kaolin and quartzsand in water (90/10% and 75/25% kaolin/quartzsand) at different solids concentrations (to avoid problems connected to the complex and changing nature of real sludges). To overcome the problem of coarse particles and impurities, sewage sludge was firstly passed through a 1,000 μm screen. The results so obtained were then compared to those obtained by a conventional rotating viscometer Haake Rheotest RV 2.1. Plots of yield stress vs. solids concentration at different tube diameters for sewage sludge are shown in Figure 1 (full lines), together with the values measured through the rotating viscometer (dotted lines).

A good agreement between the yield stress values measured with the two procedures was obtained with pipes of mid size diameter. In the case of larger diameters, the inaccuracy can be attributed to the final height of suspension comparable to the tube diameter (so the final part of the flow occurs with tube not completely filled), while in that of smaller diameters, to clogging phenomena.

Other tests have been run by using different kinds of sewage sludge (anaerobically digested dewatered, aerobically digested dewatered, reycled, anaerobically digested) at different solid concentrations. Results obtained with the Kasumeter apparatus have then been compared to those obtained by the flux curves using a conventional rotating viscometer AR 500 with plate geometry. A good linear relationship was obtained by plotting the yield stresses obtained by Bingham interpolation of viscometer data vs. yield stresses evaluated by Kasumeter, but the slope of the linear relationship resulted higher than 1. On average, the values obtained by rotating viscometer resulted about 22% higher than the corresponding ones obtained by Kasumeter. Again, the agreement is better with pipes of mid size diameters.

It follows that the boundary limit between the liquid state and the paste-like one could be easily evaluated by using simple equipment, such as the Kasumeter. Based on the above tests, it also seems that the limit of flowability could be established at approximately 50 Pa, but further research is necessary to better define this limit.

Solidity tests

A laboratory vane shear apparatus, a pocket vane shear device, and a pocket penetrometer were investigated for the evaluation of the shear strength of different waterworks sludges (Wichmann and Riehl, 1997).

Tests showed that the laboratory vane shear apparatus could be possibly taken as reference device, while a comparison between the two field tests showed that the pocket penetrometer could be more useful in the field, especially because of good handling. Figure 2 indicates a direct linkage for values from cone penetrometer and laboratory vane shear measurements. On average, the calculated shear strength values (c_u) from cone penetrometer measurements are about 20% higher than those obtained with the laboratory vane shear apparatus.

Further experiments based on the comparison of values measured, by a Vicat needle instrument, as a function of penetration into the sludge with needles of different shape and size, to those obtained through a conventional vane shear apparatus and a cone penetrometer, indicated that the Vicat needle could possibly be a good instrument to measure the solidity limit. It is an advantage of this instrument that no constant velocity is necessary during the time of the needle penetration.

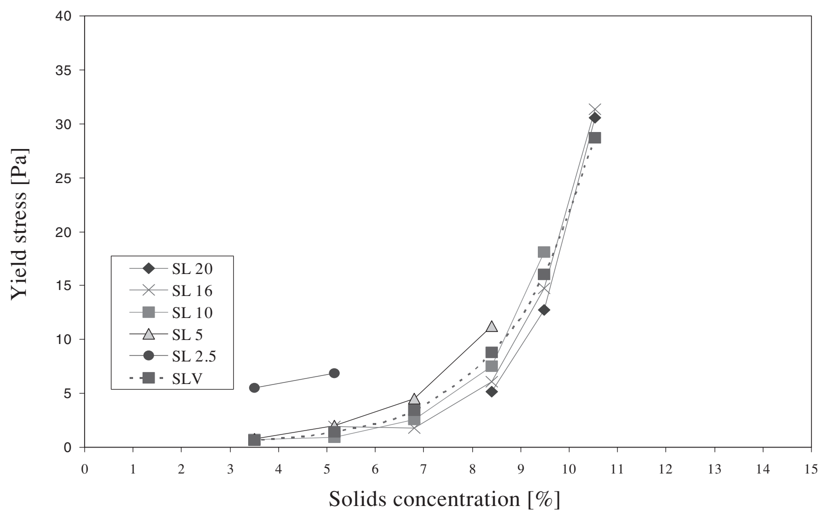

Figure 1 Yield stress vs. solids concentration (SL = sewage sludge; V = rotating viscometer) (2.5 ÷ 20 = diameter of Kasumeter pipe, mm)

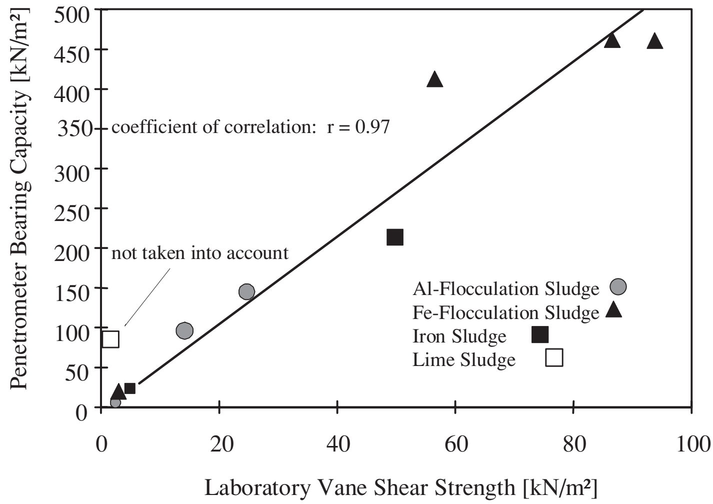

Figure 2 Cone penetrometer vs laboratory vane apparatus

Conclusions

The physical consistency that is related to the rheological properties is a parameter of fundamental importance in sewage sludge characterization as it strongly affects almost all treatment, utilization and disposal operations. In addition, references to the physical consistency are often reported in European legislation on sludge as a characteristic to be evaluated for fulfilling the regulation requirements.

However, the evaluation of rheological properties is a very complex matter which requires the preliminary definition of the sludge physical states and the standardization of the relevant measuring procedures to allow comparable and reliable results to be obtained.

Three consistency categories have been proposed for sludge, i.e. *liquid* (sludge flowing under the effect of gravity or low pressure), *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), and *solid* (sludge having a high shear resistance).

This involves the need to set up laboratory methods suitable to define the boundary limit between liquid and paste-like behaviours (*flowability*) and that between solid and paste-like behaviours (*solidity*). These procedures should also be supplemented by simple to operate and applicable in-the-field methods.

Considering that the yield stress is a typical characteristic of non-Newtonian fluids, and that the non-Newtonian behaviour becomes evident at higher solids concentration, the yield stress can be considered as indicator of sludge flowability. Tests carried out by an extrusion procedure (Kasumeter apparatus) gave yield stress results in good agreement with those obtained by a more complex one (conventional rotating viscometer), thus allowing the limit of flowability to be evaluated in a very simple way.

As far as the evaluation of solidity is concerned, tests showed that the laboratory vane shear apparatus could be possibly taken as a reference device, but the pocket cone penetrometer could be more useful in the field, especially because of good handling. Further experiments indicated that the Vicat needle could possibly be a good instrument to measure the solidity limit.

References

Baudez, J.C. (2003). Personal communication, Cemagref, Montoldre (F).

Campbell, H.W. and Crescuolo, P.J. (1983). Assessment of sludge conditionability using rheological properties. In: *Methods of Characterization of Sewage Sludge*, T.J. Casey, P. L'Hermite and P.J. Newman (eds), D. Reidel Publ. Co., Dordrecht (NL), 31–50.

CEN/TC308 (1995). *Usefulness of rheological characterization in sludge management*. Report CEN/TC308/WG2-N25.
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. and Ewing, B.B. (1967). The rheology of activated sludge. *JWPCF*, **39**(4), 543–560.
Geinopolos, A. and Katz, W.J. (1964). A study of the rotating cylinder sludge collector in the dissolved air flotation process. *JWPCF*, **36**(6), 712–721.
Koehlhoff, D. (1990). Disposal of sewage sludge in landfills, IAWPRC Sludge Mgt. Conference, Loyola Marymount Univ., Los Angeles, January 8–12.
Leschber, R. and Spinosa, L. (1998). Developments in sludge characterization in Europe. *Wat. Sci. Tech.*, **38**(2), 1–7.
Martin, A.D. (1999). Impact of sludge rheology on process design and equipment selection, *Workshop on Sludge Rheology and Reuse*, Inst. For Env. Science and Murdoch Univ., Fremantle (W. Australia), April 7.
Schulze von, B., Brauns, J. and Schwalm, I. (1991). Neuartiges Baustellenmeßgerät zur Bestimmung der Fließgrenze von Suspensionen, *Geotechnik*, **14**, 125–131.
Spinosa, L. and Lotito, V. (1999). Rheological measurements and their application in biosolids management. *Water21*, Sept.–Oct., 28–29.
Spinosa, L. and Lotito, V. (2001). The evaluation of sludge physical consistency. *Preprints of IWA Conf. "Sludge Management Entering the 3rd Millennium", Taipei (TW), March 25–28*, 84–89.
Spinosa, L., Remy, M. and Wichmann, K. (1999). Physical consistency – Measurement of sludge consistency. CEN/TC308/WG1/TG3 Report R1.
US EPA (1979). *Process design manual for sludge treatment and disposal*, EPA 625/1-79-011, Cincinnati (OH-USA).
US EPA (1984). *Use and disposal of municipal wastewater sludge*, EPA 625/10-84-003, Washington DC (USA).
Wichmann, K. and Riehl, A. (1997). Mechanical properties of waterwork sludges – Shear strength. *Wat. Sci. Tech.*, **36**(11), 43–50.