ELSEVIER

Advances in Environmental Research 7 (2003) 655–659

Advances in Environmental Research

www.elsevier.com/locate/aer

A simple method for evaluating sludge yield stress

L. Spinosa, V. Lotito*

CNR-IRSA, Via De Blasio 5, I-70123 Bari, Italy

Abstract

Three physical behaviors (liquid, paste-like and solid) can be observed with sludges. This requires laboratory procedures to define the boundary limit between liquid and paste-like behaviors (flowability). The yield stress is a typical characteristic of non-Newtonian fluids, in particular for concentrated suspensions, that can be considered as an indicator of sludge flowability. Rotating viscometers are generally used for measuring yield stress, but they are costly and difficult to operate in the field. Therefore, research has been carried out to evaluate this property by adopting simple and applicable field procedures. For experiments two synthetic suspensions of kaolin and quartz sand in water, at different solids concentrations, and an extrusion apparatus (Kasumeter) have been used, and values compared to those obtained by a conventional rotating viscometer. Results showed that the Kasumeter apparatus is able to give yield stress values comparable to those obtained by a rotating viscometer, thus allowing sludge flowability to be evaluated in a very simple way.

Keywords: Characterization; Management; Rheology; Sewage sludge, Yield stress

1. Introduction

Rheological parameters are of fundamental importance in sludge characterization, as they strongly affect almost all treatment, utilization and disposal operations, such as storage, pumping, transportation, handling, land-spreading, dewatering, drying and landfilling.

The rheological behavior of very thin sludges is Newtonian, like water, ($\tau = \mu D$, where τ is the shear stress, D the shear rate, μ the viscosity), i.e. the viscosity is independent of the flow rate and no initial resistance to overcome before movement occurs on the application of a force at rest (yield stress) is shown. Instead, the behavior of more concentrated suspensions is described as non-Newtonian. Many models are applicable. A general equation is $\tau = \tau_0 + \mu_i D^n$ (where τ_0 is the yield stress, μ_i the plastic viscosity or fluid consistency index, n the fluid behavior index), but the Bingham plastic model (with $n=1$, so no curvature of the rheogram is exhibited) should seem to be preferable, as it allows to define a unique viscosity-type coefficient (μ_B), measured by the slope of the line of shear stress vs. shear rate.

2. Background

The influence of rheological properties on sludge management operations has been studied by several authors. Following, some significant findings relevant to sludge treatments, utilization/disposal, storage and transportation are summarized.

2.1. Rheology vs. treatments

Experiments conducted by varying the food to micro-organism and the carbon to nitrogen ratios resulted in sludges with remarkable differences in rheological characteristics and not in other generally used parameters, such as solids concentration, sludge volume index, etc. (Dick and Ewing, 1967).

It is known that rheological properties affect mixing of the medium and mass exchanges between the solid, liquid and gaseous phases. Furthermore, Dick (1965) found that during thickening the extent of deviation

*Corresponding author. Fax: +39-080-531-3365.
E-mail address: spinosa@area.ba.cnr.it (L. Spinosa).

1093-0191/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S1093-0191(02)00041-2

from the prevailing theoretical design procedures, such as that based on the solid flux, as kg-solids/h/m^2, is correlable 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 evidencent that municipal sludges developed 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 selected for many unit operations, such as clarifying, thickening and dewatering, has been discussed by Martin (1999).

2.2. Rheology vs. utilization/disposal

Sludge can be applied to the land in different ways depending on its physical state. For liquid sludge methods such as spraying by sprinklers, irrigation techniques, ridge and furrows, spreading from a tank vehicle and sub-surface application can be utilized (USEPA, 1979), while sludge in the plastic/solid state can be spread with loaders, graders or box spreaders, and then plowed or disked in, or directly injected below the soil surface, by properly designed equipment (USEPA, 1984). In any case, the selection of the best equipment to be used and the optimal procedure adopted is strongly dependent on the physical consistency of the material, so the evaluation of rheological properties is essential.

Sludge disposal in sanitary landfills is commonly related to its solid concentration (~30–35%), but in many cases this is not sufficient because the corresponding vane shear strength is not sufficient enough. A reduction of the 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.

2.3. Storage and transportation

An effective optimization of sludge management requires the correct planning of the storage and transportation operations which enable the equalization between a continuous flow entering (production) and a discontinuous flow exiting (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.

In all cases, 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. Therefore, the evaluation of this property becomes necessary, to allow the optimization of sludge management operations to be achieved and to reduce costs (Wiart, 1995).

Table 1
Importance of the sludge physical states in its management

Operation	Liquid	Paste	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

(L, Low; M, Medium; H, High).

3. Physical states and measurements

The assessment of physical and mechanical characterization methods and tests firstly requires the definition of the different physical states of sludge. The following categories have been proposed (CEN/TC308, 1995):

- 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 behaviors (flowability) and that between solid and paste-like behaviors (solidity). Table 1 shows the 'applicability' of different treatment/disposal options for sludges having different physical states.

Sludge flowability is strongly related to its yield stress. Widely accepted methodologies for the evaluation of this parameter, able to give comparable and reliable results, are not available yet. At present, viscometers, or rheometers, are the instruments used for measurements. There are two types of viscometers: tube, and rotating (coaxial cylinders, rotating blades and cone-plate geometry). When using a tube viscometer, only highly 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 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,

Table 2
Results of Kasumeter tests

Test run	Solids content (%)	Density (kg/m^3)	Diameter (mm)	Suspension height (cm)
SA 1	44.67	1.404	20/16	13.7/18.2
SA 2	39.81	1.339	20/16/10	4.9/7.4/14.9
SA 3	34.83	1.303	20/16/10/5	2.0/3.0/6.9/15.8
SA 4	29.88	1.254	20/16/10/5/2.5	0.8/1.3/3.3/7.7/24.4
SA 5	24.88	1.196	16/10/5/2.5	0.3/1.5/3.9/13.8
SB 1	51.00	1.463	20/16	14.1/21.0
SB 2	47.09	1.432	20/16/10	7.5/11.0/22.2
SB 3	44.22	1.392	20/16/10/5	4.2/6.5/13.5/29.8
SB 4	41.36	1.364	20/16/10/5	2.8/3.9/8.8/20.0
SB 5	38.41	1.342	20/16/10/5	2.0/2.4/5.5/13.4
SB 6	35.41	1.297	16/10/5/2.5	2.0/3.6/9.6/29.6
SB 7	31.89	1.248	10/5/2.5	2.2/6.2/20.4
SL 1	10.53	1.038	20/16	16.0/20.5
SL 2	9.49	1.034	20/16/10	6.7/9.7/19.0
SL 3	8.40	1.031	20/16/10/5	2.7/4.0/7.9/23.7
SL 4	6.81	1.026	16/10/5	1.2/2.7/9.5
SL 5	5.15	1.020	16/10/5/2.5	1.3/1.0/4.2/29.4
SL 6	3.51	1.015	10/5/2.5	0.8/1.7/23.6

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.

The above methodologies require costly equipment and are quite complicated and difficult to run in the field, so 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 penetrometers for non-flowable ones (paste-like/solid), are preferred.

4. Experimental

Tests have been run by using two synthetic suspensions of kaolin and quartz sand in water at different solid concentrations (SA: 90/10% kaolin/quartz sand; SB:75/25%), to avoid problems connected to the complex and changing nature of real sludges, and a municipal sewage sludge (SL) at different solid concentrations, obtained through the dilution of dewatered sludge by means of a filtrate.

The extrusion apparatus (Kasumeter) used for tests consists of a cylindrical acrylic container (Ø=0.1 m; h=0.35 m; V∼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. Further details on this apparatus can be found in Schulze et al., (1991). For measurements (i) the Kasumeter is filled up with the suspension by keeping closed the end-side of the calibrated tube and by avoiding the presence of air bubbles, (ii) the end-side of the calibrated tube is opened, (iii) the chronometer started and the time measured until the flow is continuous and (iv) the height of the suspension remaining in the cylinder (h, m) is measured. The flow equation is calculated as follows:

$$Q=\pi/8*r^4/\mu*\Delta p/l*[1-(4/3*2\tau_0/r*l/\Delta p)] \qquad (1)$$

where Q is the flow rate (m^3/s), r the tube radius (m), μ the dynamic viscosity (Pa∗s), Δp the differential pressure (Pa), l the tube length (m) and τ_0 the yield stress (Pa). When the flow becomes discontinuous, Q is equal to 0, so τ_0 can be calculated through Eq. (1), considering that Δp is equal to ρgh, where ρ is the suspension density (kg/m^3) and g the gravity acceleration (m/s^2):

$$\tau_0=3/8*\rho ghr/l \qquad (2)$$

The results have been compared to those obtained by a conventional rotating viscometer Haake Rheotest RV 2.1. The following conditions were adopted:

- Gap: 0.7 mm for synthetic suspensions and 2.4 and 7.7 mm for sludge;
- shear rate: 3, 5, 9, 15, 27, 45, 81, 135 and 243 rpm (samples were firstly submitted to increasing shear rates and then vice versa);
- temperature 20 °C.

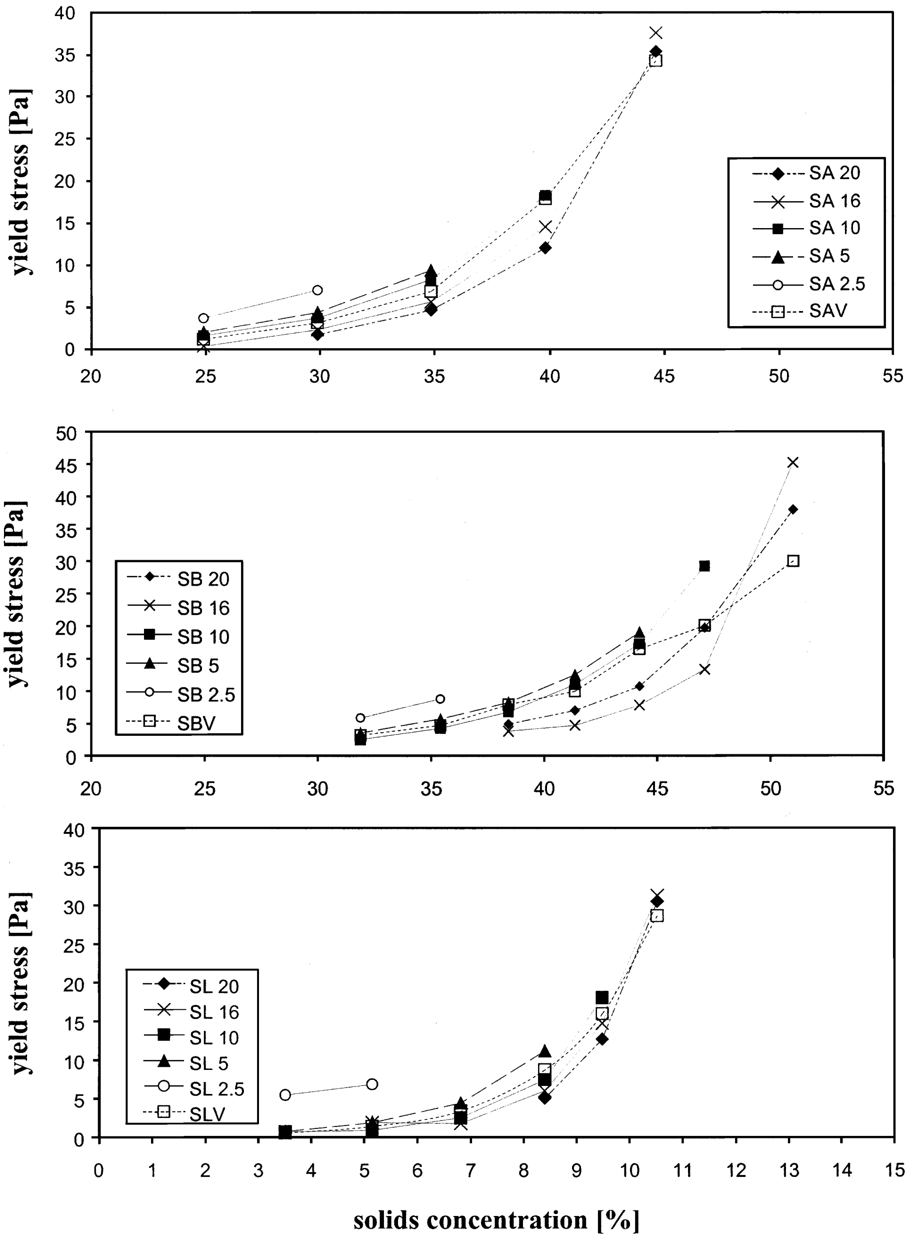

Fig. 1. Yield stress vs. solids concentration.

To overcome the problem of coarse particles and impurities, sludge was firstly passed through a 1000 μm screen.

5. Results and discussion

The values of the height of the suspension remaining in the Kasumeter, when the flow stops, are reported in Table 2 at different solids concentrations and tube diameters. The above height values allowed the corresponding values of the yield stress to be calculated through Eq. (2). Plots of yield stress vs. solids concentration at different tube diameters are shown in Fig. 1 (full lines), together with the values measured through the rotating viscometer (dotted lines).

Generally speaking, a good agreement between the yield stress values measured with the two procedures have been obtained. The agreement was better with the tube diameters of mid size. In the case of the larger diameters, the inaccuracy can be attributed to the final height of the suspension compared to the diameter of the tube (so the final part of the flow occurs with the tube not completely filled), while in the case of smaller diameters, to clogging phenomena.

Considering that the yield stress is a typical characteristic of non-Newtonian fluids and that for a sludge the non-Newtonian behavior becomes more evident at higher solid concentrations, the yield stress can be confirmed as an indicator of sludge flowability. It follows that the boundary limit between the liquid state and the paste-like one can be easily evaluated by using simple equipment, such as the Kasumeter. Based on the above tests, it seems that the limit of flowability could be established at approximately 30 Pa, but further research is clearly necessary to significatively define this limit.

6. Conclusions

Rheological characterization is a very useful tool in sludge management as it allows to predict and estimate its behavior when handling and submitting to almost all treatment and utilization/disposal operations. 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. These procedures should also be simple to operate and applicable in the field.

Tests by an extrusion procedure (Kasumeter apparatus) were shown to give yield stress results comparable to those obtained by a more complex one (conventional rotating viscometer), thus allowing the limit of flowability to be evaluated in a very simple way.

References

Campbell, H.W., Crescuolo, P.J., 1983. Assessment of sludge conditionability using rheological properties. In: Casey, T.J., L'Hermite, P., Newman, P.J. (Eds.), Methods of characterization of sewage sludge. D. Reidel Publ. Co, Dordrecht (NL), pp. 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., Ewing, B.B., 1967. The rheology of activated sludge. J.W.P.C.F. 39 (4), 543–560.

Geinopolos, A., Katz, W.J., 1964. A study of the rotating cylinder sludge collector in the dissolved air flotation process. J.W.P.C.F. 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.

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., Schwalm, I., 1991. Neuartiges baustellen-meßgerät zur bestimmung der fließgrenze von suspensionen. Geotechnik 14, 125–131.

U.S.EPA, 1979. Process design manual for sludge treatment and disposal. EPA 625/1-79-011, Cincinnati (OH-USA).

USEPA, 1984. Use and disposal of municipal wastewater sludge. EPA 625/10-84-003, Washington DC (USA).

Wiart, J., 1995. Personal communication. Agence de l'Environment et de la Maitrise de l'Energie, Angers (F).

Ludovico Spinosa graduated in Mechanical Engineering, he is Senior Scientist at Consiglio Nazionale delle Ricerche in Bari (I) in the field of sludge treatment and disposal. Author of approximately 130 scientific papers, he is Chair of the IWA Specialist Group on Sludge Management and Member of CEN/TC308 activities for standardization of sludges.

Vincenzo Lotito graduated in Chemical Engineering, since 1984 he is involved in sewage sludge treatment and disposal research, to develop standard procedures, optimize conditioning and dewatering operations and evaluate performance and reliability of sewage sludge incineration. Author of approximately 70 papers, he is member of CEN/TC308 (European Standardization Committee on sludge).