Physical Aging and Thixotropy in Sludge Rheology

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Abstract:
Sewage sludge presents a dual rheological behaviour with an abrupt change between the two regimes. Using a new technique of reconstruction of the velocity profile, the behaviour can be modelled by a unique equation including liquid and solid components but also a structural parameter. It is also rigorously demonstrated that the only one rheological behaviour in steady state in the liquid regime is a truncated power-law which can be defined only for a shear rate and a shear stress higher than a critical value, $\dot{\gamma}_c$ and τ_c. Moreover, the critical shear rate and shear stress increase with the solid content and depend on the fractal dimension of flocs which implies that thixotropic effects are all the more important as the sludge is thick and fresh.

Zusammenfassung:
Abwasserschlämme zeigen unter Belastung einen abrupten Wechsel zwischen zwei Fließverhalten. Mittels einer neuen Methode zur Rekonstruktion der Fließkurve kann dieses Verhalten durch eine Gleichung beschrieben werden, die sowohl die flüssigen und festen Bestandteile sowie einen Strukturparameter berücksichtigt. Das rheologische Verhalten für Proben im flüssigen Zustand kann durch ein modifiziertes Power-Law Model beschrieben werden, welches ausschliesslich für Scherraten und Schubspannungen über den kritischen Werten $\dot{\gamma}_c$ und τ_c liegt. Beide kritischen Werte steigen mit dem Feststoffanteil und der fraktalen Dimension von Aggregate an. Letztes deutet an, dass die thixotropen Eingeschaften bei dickflüssigen und frischen Schlämmen am ausgeprägtesten sind.

Résumé:
Les boues résiduaires présentent un comportement rhéologique dual avec un changement abrupt entre les deux régimes. A l'aide d'une nouvelle technique de reconstruction du profil des vitesses, ce comportement peut être modélisé par une seule équation incluant les composantes liquide et solides ainsi qu'un paramètre de structure. On démontre également qu'en régime permanent le comportement rhéologique ne peut être modélisé que par une loi puissance tronquée, uniquement valide au-delà d'une contrainte et d'un gradient de vitesse de cisaillement critiques. De plus, ces paramètres augmentent avec la concentration solide et dépendent de la dimension fractale des flocs, ce qui implique que les effets de thixotropie sont d'autant plus importants que la boue est fraîche et épaisse.

Key words: aging, rheology, sludge, structure, thixotropy

1 INTRODUCTION

In wastewater management, rheological measurements are presented as of special interest for mixing, chemical conditioning or dewatering [1] but sewage sludge is often seen as a complex mixture and its rheological behaviour considered to be highly dependent of the implemented treatments [2 - 3]. The literature presents a wide variety of results: sludge is always non-Newtonian [4], exhibits a yield stress [5] or not [6], is shear-thinning [7] or thixotropic [8]. Moreover, on the basis of repetitive experimental procedures and statistical analysis, the steady state behaviour was represented with the help of either a pseudo-plastic model, [3], a Bingham model, [9], or a Herschel-Bulkley model, [5, 10] but in any case a clear link was established between these models to explain the evolution from one to another.

Baudez [11] demonstrated that the behaviour of pasty sewage sludge can be divided into three parts separated by two critical stresses where hydrodynamic and particles interactions have their own predominant domain: when hydrodynamic effects are prevalent, the behaviour is well fitted by an Ostwald model whereas when both the effects coexist, the behaviour is best fitted by a Herschel-Bulkley model. Moreover, the shear stress defining the transition from Herschel-Bulk-

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the more low that the volatile fraction is small. These functions are only valid above a limited concentration which is the smallest concentration before settling occurs:

$$\tau_c = \kappa\left(\Phi - \Phi_o\right)^q$$
$$\dot{\gamma}_c = \mu\left(\Phi - \Phi_o\right)^p \qquad (6)$$

Such a result was already underlined for the elastic modulus of clay-water suspensions [22] corresponding to a percolation process associated to the yield stress appearance. Above the percolating concentration ϕ_o, a continuous network of linked particles take place (the material does not settle) and the number of particles involved in the infinite aggregate increases following an equation similar to (6) where the exponent is related to the fractal dimension of the aggregates [23]. According to Li and Ganczarczyk [24], the smaller the fractal exponent, the more the structure volume has empty spaces. This approach is fully in agreement with our values: sludge with a high volatile fraction contains more macromolecules than a mineralised sludge and consequently has a greater porosity.

In practise, thixotropic effects can alter pipe transportation by producing clogging if the wall shear stress is not high enough to maintain a homogeneous flow at least near the wall. Knowing that the shear stress is a power law function of the solid concentration, these results are a first step to help plant designers to select piping or pumping facilities based on the range of rheological properties they will anticipate.

4 CONCLUSION

The time-dependence behaviour of sewage sludge was investigated by using a new technique for reconstructing the velocity profile within the rheometer. It was shown that sewage sludge is a linear viscoelastic solid during the earliest instant of the shear. Then it starts to flow when the shear strain reaches a critical value but the flow is homogeneous only when the shear rate is higher than another critical value. Otherwise the solid structure progressively rebuilds even under shear which explains why the viscosity increases.

A rigorous analysis demonstrated that in steady state the flow can only be modelled by a truncated power-law limited by critical shear rate, $\dot{\gamma}_c$ and shear stress, τ_c. These two parameters are increasing functions of the solid concentration: the higher the solid content, the higher $\dot{\gamma}_c$ and τ_c.

In other words, the rheological behaviour of sewage sludge is governed by a competition between solid particles interactions and viscous forces as long as there is not settling. When solid particles interactions are stronger than the viscous forces, the material physically ages (flocculation) and presents some temporal effects while when viscous forces are predominant the flow is well developed and the structure memory is erased (shear rejuvenation or deflocculation).

These results allow to explain the problems encountered in pipe transportation, focusing on clogging and how to avoid it, by calculating the highest concentration to be pumped in relationship with the dimensions of the pipes.

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APPENDIX

Considering a simple Kelvin-Voigt model, which is a good approximation of the viscoelastic behaviour of sewage sludge during the earliest instants of creep tests, such that $\tau_c = G\gamma + \mu\dot{\gamma}$, we have:

$$\varphi(r) = \frac{\gamma}{2} = \left(\frac{M}{4\pi G r^2 h}\right)\left(1 - e^{-\frac{Gt}{\mu}}\right)$$

We can compute the time needed to reach the critical shear strain:

$$t_c(\tau) = -\left(\frac{\mu}{G}\right)\ln\left(1 - \frac{G\gamma_c}{\tau}\right)$$

which takes very small values for large stresses and very large values for stresses close to $\tau^* = G\gamma_c$. Note that for stresses lower than τ^*, the critical strain is never reached.

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