Municipal wastewater sludge dewaterability and the presence of microbial extracellular polymer

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Abstract Dewatering of sewage sludge is an essential and costly part of the wastewater treatment process. The presence of microbial extracellular polymer (ECP) is important for sludge flocculation, but ECP has also been shown to have a detrimental effect on the dewaterability of certain sludge types. This paper investigates the relationship between sludge dewaterability and the level of ECP present in a range of sludges obtained from 8 full-scale municipal treatment works in the UK. Sludge dewaterability was determined using the capillary suction time (CST) test, and a thermal extraction process followed by solvent precipitation was used for ECP extraction. The results indicate that for each type of sludge examined there appears to be an optimum level of ECP (raw sludge 20 mg ECP/g SS; activated sludge 35 mg ECP/g SS; digested sludge 10 mg ECP/g SS) at which the sludge should exhibit maximum dewaterability. The establishment of a trend between sludge dewaterability and the quantity of ECP present opens up the possibility of manipulating the level of microbial polymer present to aid sludge dewatering, and hence reduce plant operating costs.

Keywords Extracellular polymer; yield; sludge; dewater; capillary suction time

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Introduction

The dewatering of sewage sludge is an important part of the wastewater treatment process. Dewatering greatly reduces the volume of sludge requiring handling and disposal and is a necessary process for disposal options such as incineration. Worldwide, sludge production is increasing markedly as a result of extended sewerage and advanced wastewater treatment (Lue-Hing *et al.*, 1996). Within Europe, a major impact of the Urban Waste Water Treatment Directive is an increase in the amount of sludge requiring disposal, due to the increased levels of treatment necessary to meet discharge consents, whilst reducing the ways in which that disposal can be carried out (Davis, 1996). Knowledge concerning the factors that influence sludge dewaterability are therefore becoming increasingly important, as companies strive to deal with growing levels of waste sludge in the most economic way.

Microbial extracellular polymer (ECP) is present in varying quantities in sewage sludge, occurring as a highly hydrated capsule surrounding the bacterial cell wall and loose in solution as slime polymers (Costerton e*t al.*, 1981). ECP is thought to aid the survival of the bacterial cell by preventing dessication and acting as an ion-exchange resin, controlling the movement of ions from solution into the cell. Investigations have shown that interactions between divalent cations, in particular Ca^{2+}, inorganic particles and ECP leads to the formation and settlement of flocs in activated sludge (Bruus *et al.*, 1992), although a high amount of ECP is associated with poor settling conditions (Urbain *et al.*, 1993). In anaerobic sludges, ECP was stated to have a positive effect on the granulation process (Jia *et al.*, 1996).

One of the main influences on sludge dewaterability is particle size distribution (Karr and Keinath, 1978). Flocculation changes the particle size distribution of a sludge, binding small particles together, thereby influencing the sludge dewatering characteristics. ECP can therefore be expected to have an influence on sludge dewaterability through the high level of hydration of the polymer surrounding the bacterial cell and its role in flocculation. The role of natural ECP in the dewatering of sludge has been reviewed previously by Ryssov-Nielson (1975). At this time, a number of workers had concluded that there was a connection between the quantity of ECP present and the dewatering properties of sludge, but no-one had examined the two properties together.

To date, work concerning the relationship between ECP yield and sludge dewaterability has been limited. Novak *et al*., (1977) stated that the extractable biopolymer concentration appeared to be an important factor in determining the dewatering properties of activated sludge, but the extraction method used (high speed centrifugation and ethanol precipitation) was not sensitive and difficulty was encountered in reproducing results. The yield of ECP extracted from activated sludge using a sodium hydroxide solution was positively correlated to the sludge specific resistance to filtration (SRF) by Shioyama and Toriyama, (1985). Alteration of the amount of ECP present in sludge, by increasing the quantity of natural ECP in both aerobic return sludge and anaerobically digested sludge, has also been found to have a detrimental effect on the sludge dewatering process by influencing the SRF (Kang *et al*., 1989). There does therefore appear to be a relationship between the quantity of ECP that is present in a sludge and the sludge dewaterability; an increase in the level of ECP present causing the sludge to become more difficult to dewater.

The aim of this paper was to establish the relationship that exists between the quantity of ECP present and the dewaterability of different types of sludges obtained from operating municipal sewage treatment works. It was envisaged that for each sludge type examined, an optimum level of ECP would become apparent at which the sludge would be easiest to dewater. This value would reflect the amount of ECP required for successful flocculation of the sludge, whilst keeping to a minimum the excess water stored within the sludge floc.

Materials and methods

Sludge samples

A range of activated, raw and digested sludge samples were collected from 8 different municipal sewage treatment works, Sites A to H, in the Anglian and Southern Water Regions, UK. Sites A and B were sampled twice, before and after the introduction of chemical dosing with ferrous chloride for phosphate removal. No digested sludge sample was obtained from Site A before chemical dosing commenced. Two activated sludge samples were taken from Site B, one from each activated sludge plant. The main difference between each of these activated sludge plants was that only one plant had an anoxic zone for denitrification. There was no digested sludge available at Site F. Raw and digested sludge samples were obtained from Sites G and H but not included in the final analysis. This was due to the high levels of chemical polymer present in the Site G samples and the possibility of sea water infiltration at Site H affecting the results.

After collection, all samples were returned immediately to the laboratory where ECP extraction was carried out. At no time did a period in excess of 3 h elapse between the collection of the sludge samples and commencement of the extraction procedure. The quantity of suspended solids (SS) and volatile suspended solids (VSS) for each sludge was determined in accordance with APHA methods 2540D and 2540E respectively (APAH, 1992).

ECP extraction

All sludges were fully mixed prior to commencing the extraction procedure. ECP extraction was carried out using a thermal extraction/solvent precipitation process, similar to that of Morgan *et al*. (1990). All sludge samples were rinsed in ¼-strength Ringer's solution before the extraction process was commenced. This should have the effect of removing the loose slime polymers found in the sludge, ensuring that the ECP extracted is that directly associated with the bacteria. For the extraction process, 500 ml samples of sludge were rinsed and then resuspended in ¼-strength Ringer's solution, before being heated at 80°C for 1 h. After cooling, the polymer was separated from the sludge solids by centrifugation for 20 min at 1800 g, followed by a further 20 min at 5000 g. The extracted polymer present in the supernatant was precipitated by adding one part solvent (3 vol. acetone:1 vol. ethanol) to one part supernatant and standing overnight at 4°C. The precipitated polymer was separated from the solvent by centrifugation for 20 min at 5000 g, and any remaining solvent allowed to evaporate before obtaining the final weight of extracted polymer. The quantity of polymer extracted was related to the SS content of that sludge.

Sludge dewaterability

The capillary suction time (CST) test was used to determine the rate of water release from each of the sludges examined. The test was carried out using a Triton CST Filtrability Tester, model 200 (Triton Electronics Ltd., Essex, UK) as per manufacturer's instructions, using CST paper purchased from Triton Electronics. To enable the CST values of the different sludges to be compared, a rough correction for different solids contents was made to all CST results obtained as detailed in APHA method 2710G (APAH, 1992). The CST value for distilled water was measured for each batch of CST papers and subtracted from the sample times to improve comparisons.

Results and discussion

Yield of extracellular polymer

The yields of ECP obtained for each sludge type were comparable to those obtained by Morgan *et al*., (1990) who used a similar extraction process (Table 1). On average, the highest levels of ECP were extracted from the activated sludge samples and the lowest levels were extracted from the digested sludge samples.

Sludge dewaterability

The CST test was used as a measure of sludge dewaterability due to its simplicity and ability to provide a rapid indication of the filtrability of a sludge. One of the major drawbacks of using the CST test to compare a range of sludge types from different operational treatment works is the large variation in CST that occurs due to differences in SS concentration (Baskerville and Gale, 1968). The SS concentrations of the sludges examined were very variable (Table 2).

Relationship between sludge dewaterability and the level of ECP present

The relationship between sludge dewaterability, as measured using the CST test, and the level of microbial ECP present for activated, raw and digested sludge types is shown in Figures 1, 2 and 3 respectively. In all cases, a trend is apparent between the amount of ECP

Table 1 Comparison of the amount of ECP obtained from activated and anaerobic sludge types using a similar extraction procedure

	Activated sludge (mg ECP/g SS)	Anaerobic sludge (mg ECP/g SS)
Morgan *et al*., (1990)	70–90*	10–20
This paper	14–79	16–27

* 2 samples only

Table 2 Suspended solids concentration of all sludge samples investigated

Sewage		**Sludge SS concentration (g/l)**		
Treatment Works		**Activated**	**Raw**	**Digested**
Site A	Sample 1	6.33	29.5	-
	Sample 2	13.7	46.0	28.2
Site B	Sample 1	4.88	30.7	34.1
		8.59	–	–
	Sample 2	4.80	40.7	25.6
		10.6	–	–
Site C		5.96	14.0	22.2
Site D		7.30	19.4	27.1
Site E		5.18	32.7	15.6
Site F		8.81	27.3	–
Site G		2.46	–	–
Site H		1.54	–	–

extracted and the sludge dewaterability, but the strength of the relationship varies for each group. The strongest relationship was found between raw sludges (Figure 2) and the weakest relationship between digested sludges (Figure 3). In each case there appears to be a level of ECP at which the sludge should be easiest to dewater.

Activated sludge. There was no uniformity of operation between the activated sludge process at any of the sites sampled. Samples were obtained from plants operating at different retention times, plants with and without anoxic zones for denitrification, one plant pre-treated the waste to remove high BOD levels before the standard aeration lanes, and in some activated sludge lanes inorganic chemical addition occurred for phosphorus removal. The activated sludge samples had the lowest CSTs of all the sludge types tested. In the majority of cases, the CST obtained was very close to the CST of pure water, 0 s. This may have caused an unknown level of error to be present in the data shown, in that when the filtrability of a sludge is close to that of pure water, the linearity of the CST, with respect to sludge filtrability, decreases and tends towards zero (Baskerville and Gale, 1968).

The results obtained for the activated sludge samples are illustrated in Figure 1, from which the optimum level of ECP to give maximum sludge dewaterability can be calculated to be 35 mg ECP/g SS. Either side of this value the sludge becomes increasingly more difficult to dewater.

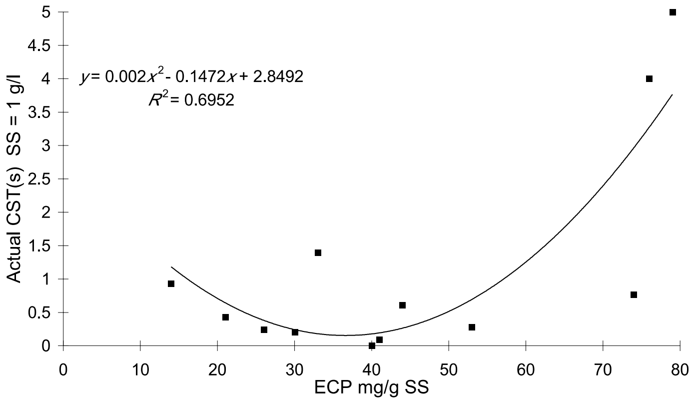

Figure 1 The relationship between the quantity of ECP present and sludge dewaterability: Return Activated Sludge

Increasing levels of ECP are initially thought to aid sludge dewaterability by improving the level of sludge flocculation. This decreases the number of small particles present in the sludge, a factor that has been shown previously to make a sludge easier to dewater (Karr and Keinath, 1978). Once a certain level of sludge flocculation has been attained, further increases in ECP become detrimental to sludge dewaterability. It is envisaged that this is due to the highly hydrated nature of the ECP retaining water within the sludge matrix, which counteracts the benefit of flocculation.

Previous work reporting the relationship between ECP yield and sludge dewaterability found that increasing levels of ECP made the sludge more difficult to dewater (Novak *et al*., 1977; Shioyama and Toriyama, 1985; Kang *et al*., 1989). In each case a different method was used for ECP extraction, and the dewatering parameter was measured using a filtration apparatus. This may account for the fact that increasing levels of ECP did not initially aid dewatering, though this is more likely to be due to the presence of inherent differences between the sludge samples used in each case.

Raw sludge. All of the raw sludge samples examined were obtained from holding tanks prior to the digestion process. Depending on the site, the sludge consisted of either just settled primary sludge, or a mixture of primary and humus sludges in unknown ratios. The strongest relationship between ECP yield and sludge dewaterability was found with raw sludge (Figure 2), correlation coefficient 0.8657. The relationship may be stronger in this instance because the CST is more likely to reflect the actual filtrability of the sludge, as the CST values obtained are not close to those of pure water.

For raw sludge, the amount of ECP required to produce a sludge that is easiest to dewater is calculated to be 20 mg ECP/g SS, which is lower than that necessary in activated sludge. Direct comparison of the results obtained for activated sludge and raw sludge is not possible because a larger sludge reservoir was used for the CST measurement of raw sludge, as raw sludge was harder to dewater. The ability of ECP to strongly retain water within the sludge matrix is likely to have a more dominant affect on raw sludge than activated sludge, because flocculation is not such a dynamic and ongoing process within the system. This is also likely to apply to digested sludges.

Digested sludge. The sludge samples came from digesters operating at mesophilic (~35°C) temperatures over a range of retention times (12–21 days), in either continuous or batch mode. The relationship between ECP yield and sludge dewaterability was not as strong for this sludge type when compared to activated and raw sludges (Figure 3). The data points

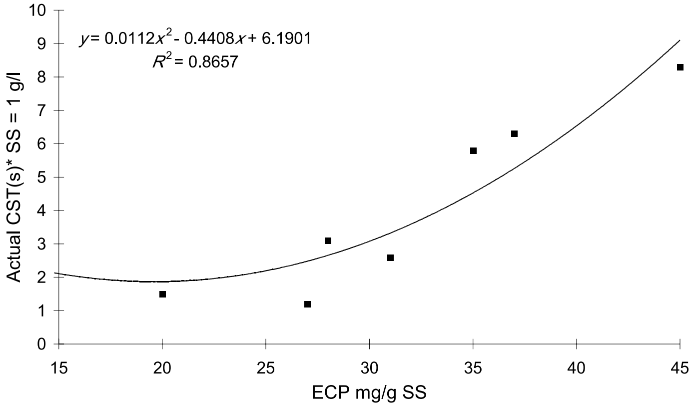

Figure 2 The relationship between the quantity of ECP present and sludge dewaterability: Raw sludge
* CSTs measured using the 18 mm sludge reservoir

themselves appeared to form two distinct lines, parallel to each other, with the relationship quoted being the average of these two trends. Examination of the manner of digester operation and sludge retention times did not show any distinct reason why the data falls into this pattern.

The level of ECP present in digested sludge is generally lower than that present in activated or raw sludge, as previously reported by Morgan *et al.* (1990). The optimum level for dewaterability was calculated to be 10 mg ECP/g SS from Figure 3. The reduction in the level of ECP present in digested sludge is thought to be due to alterations in the bacterial population as conditions within the sludge change from an aerobic to an anaerobic environment. ECP produced by bacteria in the aerobic phase may be being used as a substrate by the different bacterial populations present in the anaerobic phase. In addition, anaerobic metabolism provides a bacterial cell with less energy in comparison to aerobic metabolism. It is therefore unlikely that the cell will use this energy to produce a substance that is excreted directly into the surrounding medium.

Conclusions

The relationship between the level of extractable microbial ECP present and sludge dewaterability for a range of different sludge types, obtained from 8 full-scale municipal treatment works, was examined. Although the sites investigated were very variable in their size, mode of operation, influent characteristics and flow rate during the sampling period, a definite trend was present for each sludge type.

Activated sludge initially benefited from increasing ECP levels, with further increases in ECP being detrimental to the sludge dewaterability. For the sludges examined, the optimum level of extracted ECP for maximum sludge dewaterability was 35 mg ECP/g SS.

Increasing levels of ECP were always found to be detrimental to the dewaterability of raw and digested sludge types. For the sludges examined, the optimum level of extracted ECP for maximum sludge dewaterability was 20 mg ECP/g SS for raw sludge and 10 mg ECP/g SS for digested sludge.

The establishment of a relationship between sludge dewaterability and the quantity of ECP present in different sludge types will enable decisions to be made at plant level that ensure maximum dewaterability of the waste sludge. By altering process parameters, e.g. sludge age, retention time, digester feed composition and operation temperature, it may be possible to manipulate the level of ECP produced. At this stage, further investigation under differing conditions is necessary to confirm the validity of the relationships reported here.

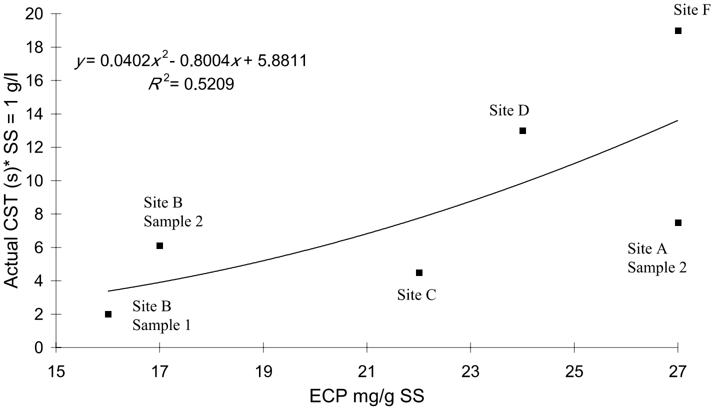

Figure 3 The relationship between the quantity of ECP present and sludge dewaterability: Digested sludge
* CSTs measured using the 18 mm sludge reservoir

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References

APHA. *Standard Methods for the Examination of Water and Wastewater* (1992). 18th edn, American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

Baskerville, R.C. and Gale, R.S. (1968). A simple automatic instrument for determining the filtrability of sewage sludges. *J. Inst. Wat. Pollut. Control*, **67**, 233–241.

Bruus, J.H., Nielsen, P.H. and Keiding, K. (1992). On the stability of activated sludge flocs with implications to dewatering. *Wat. Res.*, **26**, 1597–1604.

Costerton, J.W., Irvin, R.T. and Cheng, K.-J. (1981). The bacterial glycocalyx in nature and disease. *Ann. Rev. Microbiol.*, **35**, 299–324.

Davis, R.D. (1996). The impact of EU and UK environmental pressures on the future of sludge treatment and disposal. *J. CIWEM*, **10**, 65–69.

Jia, X.S., Furumai, H. and Fang, H.H.P. (1996). Yields of biomass and extracellular polymers in four anaerobic sludges. *Environ. Technol.*, **17**, 283–291.

Kang, S.-M., Kishimoto, M., Shioya, S., Yoshida, T., Suga, K.-I. and Taguchi, H. (1989). Dewatering characteristics of activated sludges and effect of extracellular polymer. *J Ferment. Bioeng.*, **68**, 117–122.

Karr, P.R. and Keinath, T.M. (1978). Influence of particle size on sludge dewaterability. *J. Wat. Pollut. Control Fed.*, **50**, 1911–1930.

Lue-Hing, C., Matthews, P., Nàmer, J., Okuno, N. and Spinosa, L. (1996). Sludge management in highly urbanized areas. In: *A global atlas of wastewater sludge and biosolids use and disposal*, P. Matthews (ed.), IAWQ Scientific and Technical Report No. 4, International Association on Water Quality, London, pp. 7–12.

Morgan, J.W., Forster, C.F. and Evison, L. (1990). A comparative study of the nature of biopolymers extracted from anaerobic and activated sludges. *Wat. Res.*, **24**, 743–750.

Novak, J.T., Becker, H. and Zurow, A. (1977). Factors influencing activated sludge properties. *J. Environ. Eng.*, **103**, 815–828.

Ryssov-Nielsen, H. (1975). The role of natural extracellular polymers in the bioflocculation and dewatering of sludge (literature survey). *Vatten*, **1**, 33–39.

Shioyama, M. and Toriyama, A. (1985). Yield of materials extracted from activated sludge by sodium hydroxide solution, and its relationship to specific resistance to filtration. *Journal of Japan Sewage Works Association*, **7**, 22–28.

Urbain, V., Block, J.C. and Manem, J. (1993). Bioflocculation in activated sludge: an analytical approach. *Wat. Res.*, **27**, 829–838.