



# EFFECT OF CENTRIFUGATION ON THE REMOVAL OF EXTRACELLULAR POLYMERS AND PHYSICAL PROPERTIES OF ACTIVATED SLUDGE

F. Dilek Sanin and P. Aarne Vesilind

*Duke University, Department of Civil and Environmental Engineering, Durham, NC 27708, USA*

## ABSTRACT

Activated sludge is a flocculated suspension of living and dead microorganisms enmeshed together in a polymer matrix along with some organic and inorganic materials. Extracellular polymers, main components of which are the polysaccharides, proteins, and nucleic acids, act as a protective barrier to the living microbial community, and give the floc its integrity and rigidity. These polymers have been found to affect the dewatering and settling characteristics of activated sludge. Even though they were studied considerably in the past there is not a complete understanding of the relationship between the amount of polymer and changes in the physical properties of sludge. The purpose of this research is to observe the effects of centrifugal force on the extraction of the extracellular polymers from an activated sludge and to correlate the amount of polymer extracted to the subsequent physical properties of the sludge. Centrifugal forces of 2000, 5000, 8000, 11,000, 14,000, and 16,500 G were tested for their effects on the amount of extracellular polymer collected, as well as the final properties of sludge like viscosity, filterability, compactability and supernatant turbidity. Results were evaluated in comparison to those of an uncentrifuged control waste activated sludge. Removal of extracellular polymers seems to affect the viscosity of activated sludge. Filterability, as measured by the capillary suction time instrument, was affected by the extraction of polymers to a great degree. Results of the independent tests correlated well with each other and with the amount of polymers extracted. Results of this study have important implications on sludge pumping and dewatering.

## KEY WORDS

Centrifugation, compaction, extracellular polymers, filterability, sludge, turbidity, viscosity.

## INTRODUCTION

The need for understanding the physical properties of activated sludge like settling and dewatering led to the research directed towards the understanding of bioflocculation mechanisms taking place in activated sludge systems. It is now well known that the flocculation of microbial cells in an activated sludge system is determined by the presence of extracellular polymeric material. One of the main components of this polymer matrix is the bacterial polysaccharides. It also contains the lytic products of microbial cells: proteins and nucleic acids. Extracellular polymer term is, therefore, used to refer to the overall structure formed by bacterial polysaccharides and the microbial lytic products. Li and Ganczarczyk (1990) found that extracellular polymers form the third biggest component in an activated sludge floc after the cells and water.

Busch and Stumm (1968) first used the extracellular polymers isolated from a laboratory grown activated sludge culture to flocculate negatively charged dispersions. They observed that these polymers form bridges between negatively charged inorganic and organic surfaces. Pavoni, *et al.* (1972) then observed that the removal of extracellular polymers from well flocculated bacterial suspensions resulted in stable dispersions. Further readdition of these polymers caused the reflocculation of the previously dispersed cells. The fact that extracellular polymers are highly hydrated and are able to bind a large volume of water was discovered by Forster (1983).

Extracellular polymers also found to contribute to the characteristic surface charge of sludge. This surface charge is believed to be one of the primary factors determining properties of sludge. Forster (1981, 1982 a) observed that the surface charge of sludge affects the viscosity and Goodwin and Forster (1985) found that sludge volume index was directly related to the surface charge and also the components of the extracellular polymers. Dewatering of the sludges was found to be affected by the presence of these polymers, and Kang *et al.* (1989) observed that addition of extracted extracellular polymers to different sludges increased specific filtration resistance and decreased consolidation coefficient.

Extracellular polymers have also some unique properties like binding certain cations. Polyvalent cations were found to be effective in floc growth by binding the negatively charged polymers to like polymers and to negatively charged surfaces (Busch and Stumm, 1968; Eriksson and Alm, 1991). Bruus *et al.* (1992) found that chelating the calcium ions from the activated sludge matrix results in an increase in the number of small particles and subsequently the specific resistance to filtration.

To better understand the composition and function of extracellular polymers as well as their effects on sludge properties, several techniques of polymer extraction have been developed. These techniques are physical to chemical with different degrees of severity of extraction. Some mild techniques like centrifugation do not strip polymers from sludge surfaces, whereas techniques like acid, alkali or heat extraction lyse the microbial cells, introducing intracellular materials to the extracellular medium.

Centrifugation has been used as a method of extraction for the polymeric materials from sludge surfaces as well as from the surfaces of pure and mixed culture bacteria. Busch and Stumm (1968) used a high speed centrifugation of 24,000 G to remove extracellular polymers from activated sludge surfaces. Pavoni *et al.* (1972) used a high speed centrifugation of 32,500 G for the same purpose. Both of these researches indicate that polymeric materials can be removed from sludge surfaces by centrifugation. On the other hand, Novak and Haugan (1981) demonstrated that high speed centrifugation does not strip polymers from activated sludge flocs. Similarly Brown and Lester (1980), using a speed of 33,000 G, showed that high speed centrifugation was not an effective technique for extracting polymers from both natural and laboratory grown activated sludges. High speed centrifugation was also used as the technique to recover bacterial extracellular polysaccharides from laboratory grown pure culture bacteria (Allison and Sutherland, 1987; DePhillippis, *et al.*, 1989), as well as from a soil *Pseudomonas* species (Roberson and Firestone, 1992). Besides, it is one of the standard procedures of product recovery in large industrial fermenters utilized for microbial extracellular polysaccharides production for further use in pharmaceutical and food industries (Sutherland, 1990).

The purpose of this research is to observe the effects of centrifugal force on the extraction of the extracellular polymers from an activated sludge and to correlate the amount of polymer extracted to the subsequent physical properties of the sludge.

## EXPERIMENTAL STUDY

In this study, effects of centrifugal force between 2000 and 16,500 G on the removal of polymeric materials from sludge were studied. The sludge used in this work was a waste activated sludge taken from Northside Wastewater Treatment Plant, Durham, North Carolina. The plant operation conditions at the day of sampling are summarized in Table 1.

After the waste activated sludge was sampled, it was brought to the laboratory, concentrated by gravity settling to about 1 % solids, and the supernatant was transferred to other containers for further use. Concentrated sludge was connected to an air hose and kept aerated at room temperature until the extraction experiments were finished. All of the experiments were completed within 60 hours of sampling.

During the extraction of the polymers, the following procedure was applied: sludge samples were centrifuged in two 250 mL bottles at low speed which corresponds to 1500 G for 5 minutes. This step was employed for all

samples for the removal of the sludge supernatant which may contain some macromolecules as well as the removal of slime polymers which are very loosely bound to extracellular polymer matrix (Gehr and Henry, 1983; Karapanagiotis, *et al.*, 1989). Supernatants were discarded and samples were restored to their original volumes by the addition of low ionic strength (0.005 M) phosphate buffer. The samples were then subjected to centrifugation at different speeds corresponding to 2000, 5000, 8000, 11,000, 14,000, and 16,500 G for 20 minutes at 4 °C. After centrifugation, the centrates of each bottle were removed from the top and transferred into previously marked containers. Ethanol was added in 2:1 (ethanol:supernatant) ratio to these containers, all of which were kept refrigerated overnight for the precipitation of these polymers. The precipitated polymer was recovered by centrifugation at 10,000 G for 30 minutes at 4 °C. The centrates were discarded, polymer pellets in the bottom of the bottles were washed into evaporating dishes for quantitative determination and dried at 36±1°C. Sludge pellets (at the bottom of the centrifuge bottles) after each centrifugation at the speeds listed above were resuspended in phosphate buffer (I = 0.005 M). Each of these sludge samples was analyzed for its rheological and dewatering properties, as well as its compactability upon centrifugation and supernatant turbidity following centrifugation.

TABLE 1. PLANT OPERATION CONDITIONS

Flow Rate (m <sup>3</sup> /day)	16,140
BOD <sub>influent</sub> (mg/L)	345
BOD <sub>intermediate</sub> (mg/L)*	71
MLSS (mg/L)	1420
MLVSS (mg/L)	917
Temperature (°C)	23
pH	6.8
D.O. Concentration (mg/L)	7.7
SVI (mL/g)	94

\*entering the aeration tanks

Rheological properties of sludge were analyzed by the use of a rotational viscometer having a cylindrical spindle (Brookfield, LVDVII+ with Ultra Low viscosity adaptor). Already centrifuged and resuspended sludge samples were diluted into 5 different concentrations by using phosphate buffer solution. Due to non-Newtonian flow properties of sludge, viscosity is dependent on the shear rate. For this reason viscosity measurements were conducted at six different shear rates ranging from 1.8 sec<sup>-1</sup> to 73.4 sec<sup>-1</sup> at 25 °C. Apparent viscosities corresponding to these shear rates were calculated from the ratio of shear stresses to shear rates. Since the viscosity of sludge also changes with the solids concentration, the rheological analyses described above were repeated at 5 different sludge suspended solids concentrations. All the rheological measurements were done at steady state.

Dewatering properties were measured by a capillary suction time (CST) instrument. For each sludge under investigation, CST values were measured at least six times and average CST values were used to calculate the filterability coefficient which was developed by Vesilind (1988) as given below:

$$X = \left[ (D_2^2 - D_1^2) \left( \frac{\pi d}{A P} \right) \right] \cdot \left[ \frac{\mu C}{t} \right] \quad (1)$$

where,

- X : filterability coefficient, (if it is high, filterability is easy, or vice versa)
- D<sub>1</sub>, D<sub>2</sub> : diameters of the locations of electrical sensors 1 and 2,
- d : filter paper depth,
- A : area on the bottom of collar and hence the collected sludge on the paper through which flow occurs,
- P : capillary suction, analogous to the head term in Darcy equations,
- μ : viscosity,
- C : solids concentration of the sludge,
- t : CST in seconds.

Compaction tests were done by centrifuging 50 mL sludge samples at 3000 rpm for 15 minutes. Compaction was calculated from:

$$\text{Compactability} = \left[ \frac{(H_1 / H_2)}{C} \right] \quad (2)$$

where,

$H_1$  : initial height of sludge before centrifugation,  
 $H_2$  : final height of sludge after centrifugation,

$C$  : suspended solids concentration of sludge (g/L).

Normalizing compaction with concentration was necessary because the concentrations were not strictly constant from one sample to the other.

Centrates were carefully removed from the centrifuge tubes after the compaction tests and analyzed for their turbidities with a HF Instruments Turbidimeter after the calibration of the turbidimeter with the proper standards.

Effects of centrifugation on sludge rheology, dewaterability and compactability were compared to an uncentrifuged waste activated sludge sample which was employed as a control.

The amount of polymer extracted under different centrifugal forces was controlled with the sludge's own supernatant obtained by gravity settling (1G). For this, supernatant was added to ethanol in 1:2 ratio, precipitated overnight, centrifuged at 10,000 G for 30 minutes, and dried at  $36 \pm 1^\circ\text{C}$  as previously described.

## RESULTS AND DISCUSSIONS

Results of this study indicate that by centrifugation polymeric materials can be extracted from activated sludge. As Figure 1 shows, low speed centrifugation at 2000 G extracts polymer masses more than 6 times higher than the polymeric materials that already exist in the settled supernatant. However, this effect does not increase proportionally with the increase in centrifugal force. There is only a slight increase in the amount of polymers as the centrifugal force increases. Results indicate that very high speed centrifugation (high centrifugal force) does not bring out a great amount of difference in polymer recovery as compared to slow speed centrifugation. At this point our results conflict with those of Novak and Haugan (1981) who indicate that there is a slight increase in polymer concentration in low speed centrifugation as compared to that of settled supernatant which then drops to the levels of polymer concentration in the settled supernatant with the increased centrifugal force. But from our results (Figure 1) it is obvious that even at the value of centrifugal force yielding the lowest amount of polymer extraction, polymer mass was about at least 6 times as high as that in the settled supernatant.

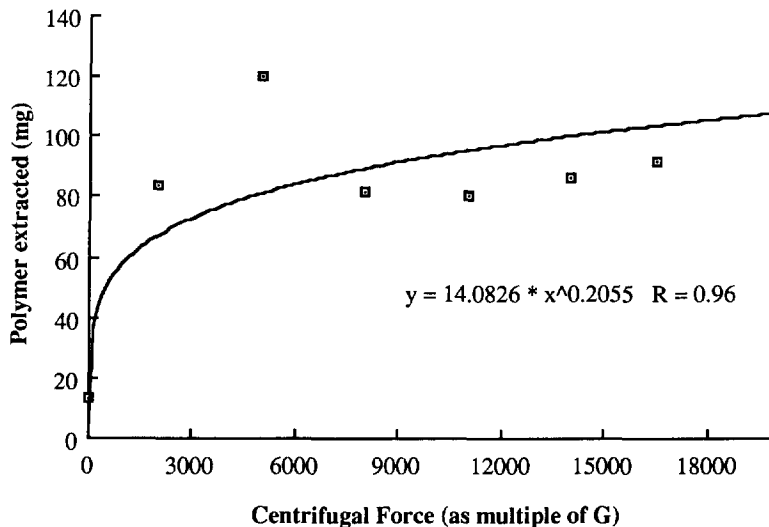


Figure 1. Variation of polymer extracted with the centrifugal force applied.

A sample rheogram, which was produced for the sludge centrifuged at 16,500 G, is given in Figure 2. Even though Figure 2 represents just one of the rheograms among more than 35 rheograms produced during this study, it typically represents the relationship between shear stress and shear rate that was observed throughout this study. The typical relationship observed is of a power law relationship in the form given below:

$$\tau = K (\dot{\gamma})^n \quad (3)$$

where,  $\tau$  : shear stress,  
 $K$  : fluid consistency index,  
 $\dot{\gamma}$  : shear rate,  
 $n$  : flow behavior index.

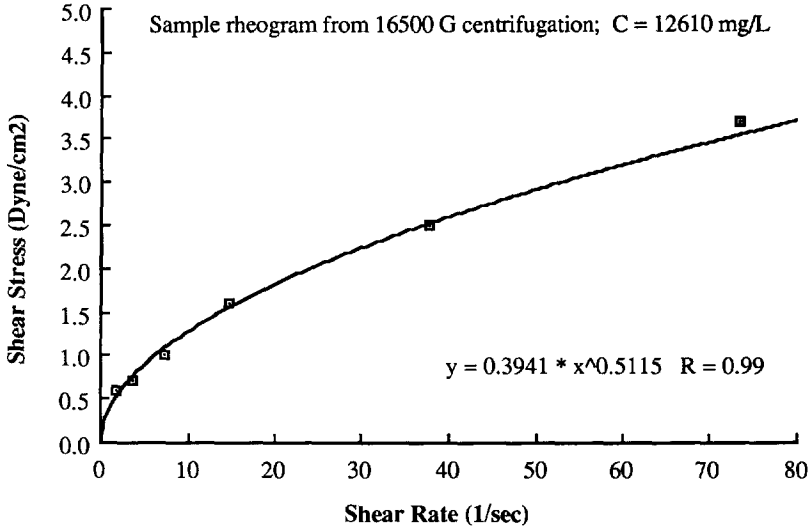


Figure 2. Presentation of a selected rheogram

The data fit well to the power law relationship. Sludge solids concentration and the condition of sludge (like centrifugation conditions in this research) are the major factors governing the values of  $K$  and  $n$  in Equation (3). Figure 3 shows the concentration dependent apparent viscosity (hereafter called viscosity) for the control waste activated sludge under investigation as well as some of the centrifuged sludges. For simplification purposes results are only presented for three of the centrifuged samples. The others are in good agreement with the data presented. From the statistical analysis of data, it is observed that viscosity depends on sludge suspended solids concentration in an exponential fashion. For both the control waste activated sludge and the centrifuged sludges the relationship is of the form:

$$\mu = A e^{(B \cdot C)} \quad (4)$$

where,  $\mu$  : apparent viscosity,  
 $C$  : suspended solids concentration of sludge,  
 $A, B$  : regression coefficients.

Table 2 lists the values of  $A$  and  $B$  as well as the correlation coefficients valid for the data. If Figure 3 is examined by keeping the solids concentration constant, it can be seen that there is a considerable reduction in viscosity by centrifugation at 2000 G. This reduction becomes more significant if the sludge concentration is higher than 10000 mg/L; the reduction being 26 % at 12000 mg/L and about 30 % at 15000 mg/L suspended solids concentration. The reductions in viscosity becomes gradually smaller as the centrifugal force is increased. In order to be able to see centrifugation dependent viscosity reductions, Figure 4 is drawn using the data from Figure 3 and the regression results given in Table 2. There is only an incremental reduction in viscosity (3 %) by the increase in centrifugal force from 2000 to 16,500 G at both solids concentrations. The significant reduction

in viscosity at 2000 G and slight gradual reduction later in the range of 2000 to 16,500 G correlate quite well with the behavior of the amount of polymer extracted (Figure 1) at these centrifugal forces. High speed centrifugation does not contribute much to polymer extraction nor to viscosity reduction.

TABLE 2. LIST OF REGRESSION PARAMETERS CALCULATED FOR EQUATION (4).

Sludge Sample	A	B	r
Control waste activated sludge	0.94	$1.6 \times 10^{-4}$	0.999
Sludge centrifuged at 2000 G	0.92	$1.4 \times 10^{-4}$	0.999
Sludge centrifuged at 5000 G	0.97	$1.3 \times 10^{-4}$	0.998
Sludge centrifuged at 8000 G	1.06	$1.3 \times 10^{-4}$	0.979
Sludge centrifuged at 11,000 G	0.98	$1.3 \times 10^{-4}$	0.999
Sludge centrifuged at 14,000 G	0.92	$1.3 \times 10^{-4}$	0.999
Sludge centrifuged at 16,500 G	0.99	$1.3 \times 10^{-4}$	0.999

For systems like glass beads and coal slurries (Leong and Boger, 1990), the flocculated nature of suspensions increase both the viscosity and bring out a more pronounced non-Newtonian behavior. Extracting at least part of the activated sludge extracellular polymers by centrifugation probably causes the breakup of large activated sludge flocs resulting in reductions in viscosity.

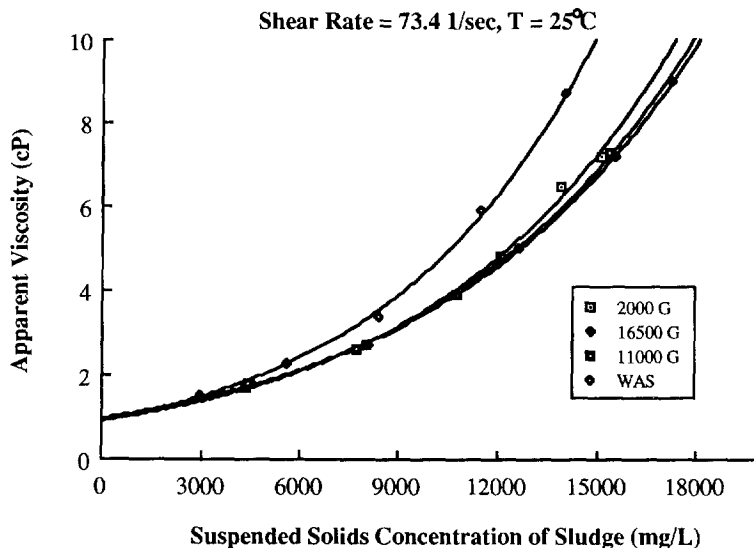


Figure 3. Variation of viscosity with suspended solids concentration of sludge at different centrifugal forces.

The results of filterability tests are given in Figure 5. Filterability values as calculated by Equation 1 shows a decrease of 50 % after centrifugation at 2000 G as compared to control activated sludge. This reduction continues as the centrifugal force is increased, however, the difference is not as dramatic as it is for the control compared to 2000 G centrifugation. Figure 5 is also in good agreement with Figure 1, indicating that the amount of polymer extracted correlates well with the reduction in filterability of the sludge. Karr and Keinath (1976) found that the one very important property of sludge determining dewaterability is its particle size. The smaller sized particles, if they are high in number, are able to clog both the filter paper pores and the sludge cake itself making the dewatering difficult. Our results show that waste activated sludge is very readily filterable, but as polymers are extracted from sludge, and large and readily filterable flocs are broken down into smaller ones, the filterability of sludge deteriorates significantly. Bruus, *et al.* (1992) observed a similar response when they used a chemical extraction technique for the extracellular polymers. Addition of EGTA chelated calcium ions in the

sludge which were binding the polymers to each other and to other negatively charged surfaces like flocs or cells. This caused a dramatic reduction in filterability and an increase in supernatant turbidity due to the creation of smaller particles. Similarly, the results of turbidity tests shown in Figure 6 support the concept of creation of smaller particles by polymer extraction, and a deterioration in supernatant turbidity.

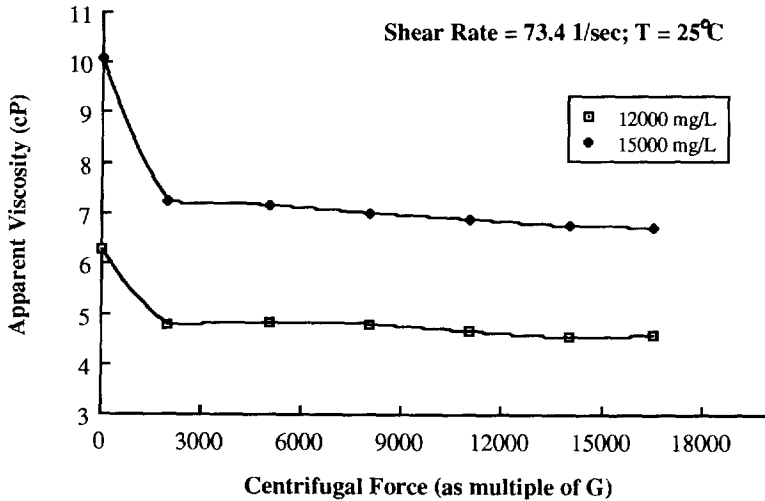


Figure 4. Effect of applied centrifugal force on the viscosity of sludge at two different solids concentration.

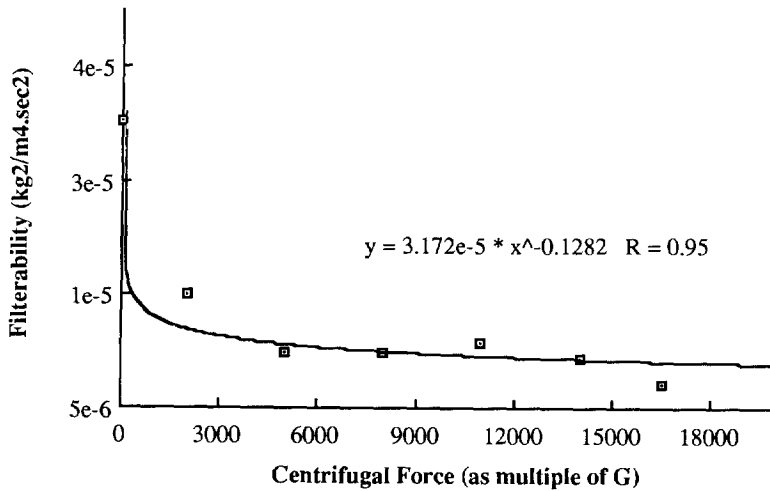


Figure 5. Effect of applied centrifugal force on the filterability of sludge

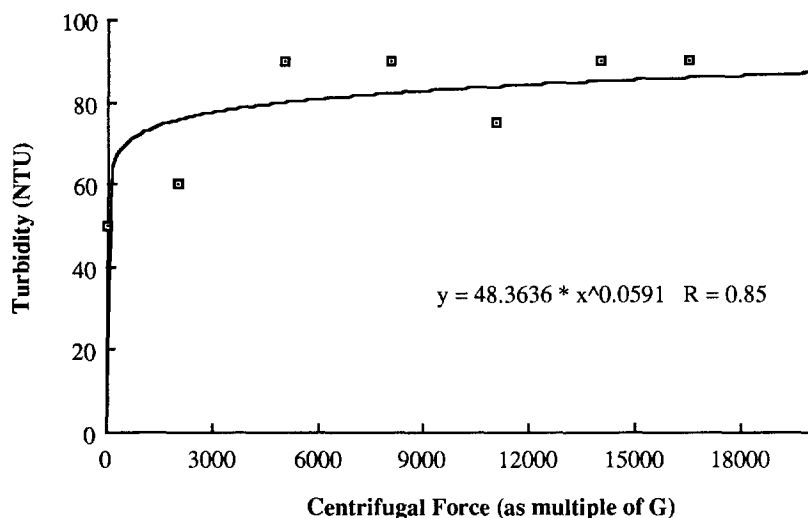


Figure 6. Illustration of variation of centrate turbidity with the application of different centrifugal forces.

Compactability data as given in Figure 7 does not show much variation with the centrifugal force applied during polymer extraction. This may originate from the fact that polymers extracted only constituted a certain portion of the total mass. Even though we believe that the extracellular polymers are highly compactable, extraction does not yield much difference in compactability values. These results can be explained: 1. polymers extracted constitute only a small portion in mass and may not contribute a great difference in compactability; 2. gas bubbles in the centrifuge tubes may have affected our results; 3. compaction technique employed was the least sensitive technique of all of the techniques we used, even though the effect of extracting the polymers was readily identifiable in filtration, viscosity and turbidity tests, it went undetected in compaction tests.

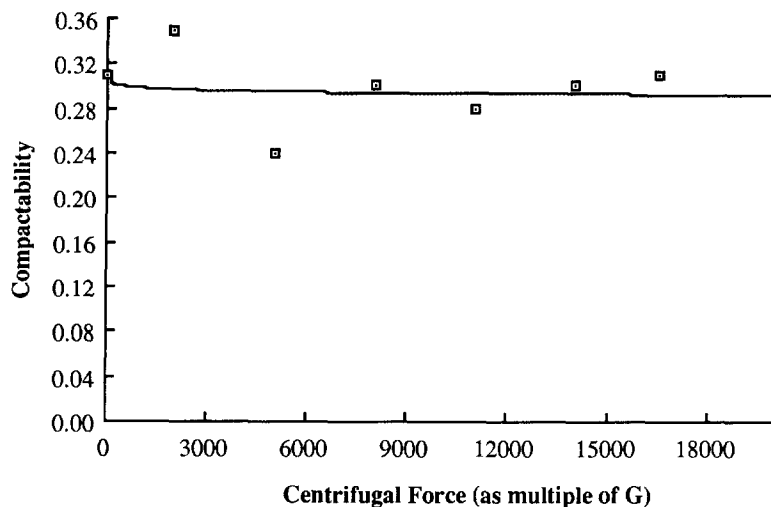


Figure 7. Variation of sludge compactability with the applied centrifugal force.



From all of the tests conducted in this study, filterability is the sludge property which is most susceptible to the removal of polymers. Viscosity reductions are not as great as the reductions in filterability at least in the solids concentration range studied here. Filterability is one parameter which tends to be very much affected by the breakdown of the flocs into smaller flocs and particles. For bringing out this kind of a dramatic effect on the viscosity in a sludge having an average solids content of 10 to 15 g/L, a stronger technique of extraction should be employed. As shown in Figure 3, effect of centrifugation on viscosity becomes much more pronounced as the solids concentration is increased. It seems very plausible that the higher the concentration is the higher the number of flocs and associated polymers are. For highly concentrated sludges, (above 20 - 30 g/L), centrifugation itself may cause a considerable reduction in viscosity. It is believed that a high degree of deflocculation will reduce the viscosity and the problems associated with the pumping of concentrated sludges originating from the non-Newtonian behavior. It is not suggested here that centrifugation extracts all or most of the extracellular polymers associated with the sludge matrix. Data from this study show that polymers extracted are 2 % of the total sludge solids. This is a low value as compared to extracts of some other techniques listed by Forster (1982 b) like boiling and alkali treatment, heat extraction, steaming, sonication and even some cases of extractions by centrifugation. What is aimed in this study is to demonstrate that even if the extraction technique is mild it still translates into the physical properties of sludge through the removal of polymers. Results of this study show that the extracted polymer quantity is in good correlation with the reduction in viscosity and filterability as well as increase in supernatant turbidity.

Sludge floc matrix is complicated in structure and composition. So are the extracellular polymers which consist of different components having various physical-chemical properties. Depending upon the chemical composition and nature of the components polymers can make bonds with varying strengths. There are always loosely bound polymers which cause attachment with minimum energy. These are readily removable at low speeds of centrifugation. Extracellular polysaccharides can have hydrogen bonds as well as long range bonds (Christensen, 1989) and they interact with polyvalent cations like calcium and bridges between the smaller flocs or particles with each other. As Urbain *et al.* (1993) noted, extracellular polymers have also hydrophobic components like lipids and proteins, which offer greater possibilities of bonding. Both the hydrophobic polymers and hydrophobic compartments on cell surfaces can bind strongly by hydrophobic bonding. Further, at the innermost part of the floc there are capsular polysaccharides tightly encapsulating the bacteria. In activated sludge there are several bacteria, like *Zooglea*, *Klebsiella*, *E. coli*, which are able to produce capsular polysaccharides (Roth, 1977). Obviously these polymer systems having different components create bonds of different strengths. The quantity and the quality of the extracts depend on how strong the bonds are. Loosely bound polymers can be extracted by mild techniques of extraction like centrifugation and cause a certain degree of deflocculation as indicated by the results of this study. Chelating the polyvalent ions (like calcium which is very abundant in water systems and highly likely to be involved in bioflocculation) causes further deflocculation so chelating agents combined with centrifugation may be a potential technique of removing these polymers. However, capsular polysaccharides and the tightly bound polymers are not easy to extract and it is almost impossible to remove them without damaging the cells. When the cells are damaged neither quantitative nor qualitative estimates should be done on the extracted polymers. Due to the damage to the cells and sludge itself, measured physical properties cannot closely represent the true properties of activated sludge flocs.

## CONCLUSIONS

1. Centrifugation extracts easily extractable extracellular polymers (which are not tightly bound). This is indicated by at least a six times increase in the mass of ethanol precipitated material after centrifugation as compared to that in a settled sludge supernatant. High speed centrifugation does not improve polymer extraction to a greater degree as compared to low speed centrifugation.
2. There is a viscosity reduction with the amount of polymer extraction by centrifugation. This can be explained by floc breakup into smaller flocs resulting in a viscosity reduction.
3. The most dramatic effect of the removal of extracellular polymers is observed on the values of filterability. Removal of the polymers, even partly, caused the release of small particles capable of clogging the filtration channels in the filter paper and the sludge cake.
4. Compactability of sludge, even though believed to be highly affected by the presence and amount of polymers, does not show much variation as the polymers are extracted from the floc matrix.
5. It is not possible at present to remove all of the extracellular polymers from sludge surfaces without damaging the cells and changing the characteristics of sludge significantly.

## REFERENCES

- Allison, D. G. and Sutherland, I. W. (1987). The role of exopolysaccharides in adhesion of freshwater bacteria. *Journal of General Microbiology*, v. **133**, n. 5, pp. 1319-1327.
- Brown, M. J. and Lester, J. N. (1980). Comparison of bacterial extracellular polymer extraction methods. *Applied and Environmental Microbiology*, v. **40**, n. 2, pp. 179-185.
- Bruus, J. H., Nielsen, P. H., and Keiding, K. (1992). On the stability of activated sludge flocs with implications to dewatering. *Water Res.*, v. **26**, n. 12, pp. 1597-1604.
- Busch, P. L. and Stumm, W. (1968). Chemical interactions in the aggregation of bacteria; Bioflocculation in waste treatment. *Environmental Sci. and Technol.*, v. **2**, n. 1, pp. 49-53.
- Christensen, B. E. (1989). The role of extracellular polysaccharides in biofilms. *J. Biotechnology*, v. **10**, n. 3/4, pp. 181-202.
- De Philippis, R., Sili, C., Vincenzini, M., and Materassi, R. (1989). Exocellular polysaccharide production by a nitrogen fixing cyanobacterium. In: *Biomedical and Biotechnological Advances in Industrial Polysaccharides*. V. Crescenzi, I. C. M. Dea, S. Paoletti, S. S. Stivala, and I. W. Sutherland (eds.) Gordon and Breach Science Publishers S. A., New York, N.Y., pp. 203-210.
- Eriksson, L. and Alm, B. (1991). Study of flocculation mechanisms by observing effects of a complexing agent on activated sludge properties. *Wat. Sci. Tech.*, v. **24**, n. 7, pp. 21-28.
- Forster, C. F. (1981). Preliminary studies on the relationship between sewage sludge viscosities and the nature of the surfaces of the component particles. *Biotechnology Letters*, v. **3**, n. 12, pp. 707-712.
- Forster, C. F. (1982 a). Sludge surfaces and their relation to the rheology of sewage sludge suspensions. *J. Chem. Tech. Biotechnol.*, v. **32**, n. 8, pp. 799-807.
- Forster, C. F. (1982 b). Biopolymer yields from activated sludge and their relation to the operation of treatment plant. *Biotechnology Letters*, v. **4**, n. 10, pp. 655-660.
- Forster, C. F. (1983). Bound water in sewage sludges and its relationship to sludge surfaces and sludge viscosities. *J. Chem. Tech. Biotechnol.*, v. **33B**, n. 1, pp. 76-84.
- Gehr, R. and Henry, J. G. (1983). Removal of extracellular material; Techniques and pitfalls. *Water Res.*, v. **17**, n. 12, pp. 1743-1748.
- Goodwin, J. A. S. and Forster, C. F. (1985). A further examination into the composition of activated sludge surfaces in relation to their settlement characteristics. *Water Res.*, v. **19**, n. 4, pp. 527-533.
- Kang, S., Kishimoto, M., Shioya, S., Yoshida, T., Suga, K., and Taguchi, H. (1989). Dewatering characteristics of activated sludges and effect of extracellular polymer. *J. Fermentation and Bioengineering*, v. **68**, n. 2, pp. 117-122.
- Karapanagiotis, N. K., Rudd, T., Sterritt, R. M., and Lester, J. N. (1989). Extraction and characterisation of extracellular polymers in digested sewage sludge. *J. Chem. Tech. Biotechnol.*, v. **44**, pp. 107-120.
- Karr, P. R. and Keinath, T. M. (1978). Influence of particle size on sludge dewaterability. *Journal WPCF*, v. **50**, n. 8, pp. 1911-1930.
- Leong, Y. and Boger, D. V. (1990). Surface chemistry effects on concentrated suspension rheology. *J. Colloid and Interface Sci.*, v. **136**, n. 1, pp. 249-258.
- Li, D and Ganczarczyk, J. J. (1990). Structure of Activated sludge flocs. *Biotech. and Bioeng.*, v. **35**, n. 1, pp. 57-65.
- Novak, J. T. and Haugan, B. (1981). Polymer extraction from activated sludge. *Journal, WPCF*, v. **53**, n. 9, pp. 1420-1424.

- Pavoni, J. L., Tenney, M. W., and Echelberger, W. F. Jr., (1972). Bacterial exocellular polymers and biological flocculation. *Journal WPCF*, v. 44, n. 3, pp. 414-431.
- Roberson, E. B. and Firestone, M. K. (1992). Relationship between desiccation and exopolysaccharide production in a soil *Pseudomonas* sp. *Applied and Environmental Microbiology*, v. 58, n. 4., pp. 1284-1291.
- Roth, I. L. (1977). Physical structure of surface carbohydrates. In: *Surface Carbohydrates of the Prokaryotic Cell*. I. W. Sutherland (ed.), Academic Press, London, pp. 8-20.
- Sutherland, I. W. (1990). *Biotechnology of Microbial Exopolysaccharides*. Cambridge Studies in Biotechnology 9, Cambridge University Press, Cambridge, pp. 80-88.
- Urbain, V., Block, J. C., and Manem, J. (1993). Bioflocculation in activated sludge: an analytic approach. *Water Res.*, v. 27, n. 5, pp. 829-838.
- Vesilind, P. A. (1988). Capillary suction time as a fundamental measure of sludge dewaterability. *Journal WPCF*, v. 60, n. 2, pp. 215-220.