Re-submitted to: *Separation and Purification Technology* **(SEPPUR-D-06-00174)**
Date: May 22, 2006

Membrane Fouling in a Submerged Membrane Bioreactor (SMBR): Characterisation of the Sludge Cake and its High Filtration Resistance

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Abstract

The attachment of sludge cake to the membrane surface is the main cause of the fouling problem in the submerged membrane bioreactors (SMBR) used in biological wastewater treatment. In this laboratory study, the sludge cake deposited on the membrane was found to have a specific filtration resistance of the order of 10^{14} m/kg, which is much greater than expected for sludge cake formed during the dewatering of activated sludge. The filterability tests showed that the cake sludge removed from the fouled membrane of the SMBR had an average specific filtration resistance of 4.9×10^{13} m/kg, whereas the sludge cake of the SMBR bulk sludge had an average filtration resistance of only 1.9×10^{11} m/kg. Detailed chemical analysis showed there was a pool of biopolymer clusters (BPC) that was trapped within the sludge cake on the membrane. These clusters could be readily separated from the cake sludge by stirring it into a suspension. The abundance of non-filterable BPC as measured by the total organic carbon (TOC) in the suspended solids (SS) was about 10.3 mg/g-SS for the cake sludge, in comparison to 0.4 mg/g-SS for the bulk sludge. When the BPC were removed from the cake sludge, the filtration resistance of the cake sludge could be reduced considerably from 4.9×10^{13} to 8.4×10^{12} m/kg. It is argued that the BPC are a special form of organic matter formed by affinity clustering of the free extracellular polymeric substances (EPS) and soluble microbial products (SMP) in the sludge cake deposited on the membrane surface. The accumulation of BPC within the pores of the sludge cake is mostly responsible for the unusually high filtration resistance of the cake sludge during the SMBR operation.

Keywords: Membrane bioreactor (MBR); Membrane filtration; Membrane fouling; Biopolymer clusters (BPC); Sludge cake; Water purification; Wastewater treatment.

1. Introduction

The membrane bioreactor (MBR) process has been deemed to be a promising technology for wastewater treatment and water reclamation [1,2]. Compared to the conventional activated sludge process, an MBR system features advantages such as a small footprint, high quality effluent, a low sludge production rate and easy manipulation of the sludge retention time [1,3,4]. With its effective biomass-effluent separation by membrane filtration, the MBR process is expected to lead the next generation of biological wastewater technologies. However, membrane fouling is still the major limitation to the large-scale application of the MBR process [5,6]. Physical rinsing and chemical cleaning have to be applied frequently in the operation of an MBR, which increases the operation cost and shortens the life of the membrane. Thus, there is a need to obtain a better characterisation of the fouling phenomenon to develop more effective design and operation strategies for fouling control in MBR applications.

In the case of submerged membrane bioreactors (SMBR), the main cause of fouling problems is sludge cake formation on the membrane surface [7-10]. Membrane filtration involves the inevitable deposition of sludge on the membrane surface. The uneven distribution of aeration intensity on the membrane for surface cleaning leads to a partial sludge cake coverage, which initiates a progressive sludge cake growth on the membrane. The sludge cake apparently originates from the biomass of the bulk sludge of the MBR suspension. However, the sludge cake layer attached to the membrane surface appears to have a much greater filtration resistance than would be expected for the sludge cake of activated sludge. A sludge cake formed on the MBR membrane with a thickness of less than 1 mm would have a filtration resistance of 1.7×10^{13} 1/m, which could cause a pressure drop of about 0.5×10^{5} Pa for a low effluent flux of 0.25 $m^3/m^2 \cdot d$ or less [2]. In comparison, in the dewatering of normal activated sludge by vacuum filtration, a sludge cake of 1 cm or so

would cause a pressure drop of no more than 0.1×10^5 Pa. A detailed examination shows that the sludge cake deposited on the membrane surface in the SMBR process has a filtration resistance of around 10^{14} m/kg [9], which is nearly three orders of magnitude higher than the value of 10^{11} m/kg or less that has been determined for activated sludge during dewatering [11].

Therefore, a sludge cake formed by direct dewatering of the bulk activated sludge should have a much lower filtration resistance than has been reported for the sludge cake that attaches to the membrane during the MBR operation. The main cause of the difference between the filtration resistance of the bulk sludge and that of the cake sludge is unclear, and has not previously been investigated. It has been suggested that, rather than the biomass in the sludge, the organic materials in the supernatant may have a more decisive effect on the filterability of the sludge suspension [11,12]. This study investigates the filtration characteristics of the sludge cake attached to the membrane surface and the bulk sludge in the MBR suspension. The filterability and composition of the liquid phase and solid phase components of both sludge solutions are identified. The findings provide a critical insight into the membrane fouling mechanism in the MBR process, and in particular into the interaction between biopolymers and biomass flocs in sludge cake formation and the high filtration resistance of the sludge cake.

2. Methods and Materials

2.1. Set-up and operation

A lab-scale submerged MBR was used for the characterisation of membrane fouling. The set-up and operation of the SMBR was similar to that described in previous studies [2,13]. A 0.4-μm polyethylene hollow-fibre membrane module with a surface area of 0.2 m^2

(Mitsubishi Rayon) was immersed in an activated sludge reactor to form an SMBR with a working volume of 5 L. The effluent was drawn through the membrane by a suction pump in an intermittent mode with a filtration/idle-cleaning ratio that was set to 18 min:2 min. Aeration was provided at the bottom of the reactor for continuous membrane cleaning, and the trans-membrane pressure (TMP) of the effluent was monitored by a manometer in mm Hg. The influent to the MBR was a glucose-based synthetic wastewater that was prepared according to the basic recipe given in the Environmental Engineering Process Laboratory Manual of AEESP [14]. Actual domestic sewage that was collected from a local wastewater plant (Stanley Sewage Treatment Works, Hong Kong) was added into the influent at a ratio of around 10% of the organic input to supply the trace elements for microbial growth. $NaHCO_3$ was added to the influent at 50 mg/L or higher to maintain the pH of the MBR suspension in the neutral range of between 6.5 and 7.5. The biomass concentration in the suspended sludge (SS) varied from 8 to 12 g/L and the corresponding organic loading in chemical oxygen demand (COD) was between 0.2 to 0.3 g COD/g-SS·d. The sludge residence time (SRT) in the reactor was approximately 20 days.

The filtration resistances of the membrane during the MBR operation were determined from the correlations between the TMP and the flow rate during normal filtration of water production and reverse filtration with clean water. The permeate flux, J, as driven by the TMP (ΔP) of the MBR can be described by Darcy's law [15] as $J = \Delta P / (\mu R)$ for the effluent filtration, or

$$J = \frac{\Delta P}{\mu(R_m + R_p + R_{sc})}, \qquad (1)$$

where μ is the viscosity of the permeate (water), and R_m, R_p and R_{sc} are the intrinsic resistance of the membrane, the membrane pore fouling resistance and the resistance of the sludge cake attached to the membrane surface, respectively. During reverse filtration (backwashing) by

pumping water into the MBR through the membrane, the TMP was found to drop dramatically. The new flux-TMP correlation in terms of the respective R'_m, R'_p and R'_{sc} during reverse filtration becomes

$$J' = \frac{\Delta P'}{\mu(R'_m + R'_p + R'_{sc})}. \quad (2)$$

It is reasonable to assume that $R_m = R'_m$ and $R_p = R'_p$ for the same membrane in the MBR operation. During reverse filtration, the sludge cake becomes much looser without the backing of the membrane, which leads to great reductions in the TMP and sludge cake resistance. It may be approximated that $R'_{sc} \approx 0$, and hence the other filtration resistances can be estimated by

$$R_p = \frac{\Delta P'}{\mu J'} - R_m \text{ and} \quad (3)$$

$$R_{sc} = \frac{\Delta P}{\mu J} - (R_m + R_p). \quad (4)$$

The hollow-fibre membrane has a resistance of $R_m = 1.5 \times 10^{11}\ m^{-1}$ [9]. By recording J versus TMP and then J' versus TMP′, the filtration resistances R_p and R_{sc} can be determined. The measurement of reverse filtration was taken at different time intervals dependent on the membrane fouling rate from once a hour to twice a day. The pressure of reverse filtration, which would vary with the flux, was normally less than 20 kPa. In addition, the specific resistance (r, m/kg) of a sludge cake with a biomass density of M_{sc} (kg/m^2) or a thickness of ξ (m) on the membrane can be estimated by $r = R_{sc} / M_{sc}$, or

$$r = \frac{f R_{sc}}{\xi \rho_{sc}}, \quad (5)$$

where ρ_{sc} and f are the wet density and the ratio of the wet weight to the dry weight (SS) of the sludge cake, respectively. For activated sludge, the values of $\rho_{sc} = 1.06 \times 10^3$ kg/m^3 and $f = 3.45$ have been previously determined [16].

2.2 Filtration resistances of the sludge cake layer attached to the membrane and the sludge cake formed from the bulk sludge.

When the membrane was severely fouled by the sludge cake, the cake sludge (CS) which is the mass of the sludge cake removed from the membrane, was carefully scraped off from the membrane surface using a spatula. The recovered CS was resuspended and dispersed by stirring into a 0.05% NaCl solution that had a similar salinity to the mixed liquor in the MBR. The CS suspension had an SS concentration of around 10 g/L, which was similar to the bulk sludge of the MBR suspension. A bulk sludge (BS) sample was withdrawn from the reactor and characterised for comparison with the cake sludge.

The two sludge suspensions (CS and BS) were measured for their resistance to filtration. In addition, 300 mL of each of the sludge suspensions was separated by one hour of sedimentation into the supernatant and the settled sludge mass. After the collection of the supernatant, the settled sludge was resuspended in 0.05% NaCl solution to its original volume of 300 mL. The filtration resistances of the supernatant and the new suspension of the settled sludge were also measured. The specific resistance to filtration of a sludge sample was determined by the filterability test following the method of Wisniewski and Grasmick [17]. The test was conducted in a 400-mL stirred cell (Model 8400, Amicon) using a 0.22-μm flat-sheet cellulose membrane filter (GSWP 09000, Millipore). The stirred cell was filled with 250 mL of the sample liquor, and a constant pressure was applied by pressurised nitrogen from a gas cylinder. The production of filtrate under pressure was continuously recorded by

an electric balance that was connected to a data logger. The specific resistance to filtration (r, m/kg) can be calculated [18] by

$$r = \frac{2\,000 A^2\, \Delta P\, b}{\mu C} \quad , \tag{6}$$

where ΔP (25 kPa) is the pressure applied, A (0.00418 m^2) is the filtration area, C is the total suspended solids (kg/m^3), and b (s/m^6) is the time-to-filtration ratio, which is the slope of the curve that is obtained by plotting the time of filtration to the volume of filtrate ratio (t/V) versus the filtrate volume (V).

2.3. Analysis of the sludge composition

The two sludge suspensions (CS and BS) were centrifuged (5810R, Eppendorf) in 50-mL tubes at 4000 g for ten minutes to separate the liquid and the biomass. The centrate liquor was recovered for analysis of its composition. The sludge pellet in the tube after dewatering was resuspended by a vortex mixer (Maxi Mix II, Thermolyne) in a 0.05% NaCl solution to its original volume of 50 mL. A mild heat extraction method was used, in which the suspension was heated to 50˚C for 25 minutes in a water bath to extract the extracellular polymeric substances (EPS) from the biomass. After centrifugation at 4000 g for 15 minutes, the supernatant collected was regarded as the EPS extraction of the sludge.

For both the CS and BS suspensions, the sludge centrates and the EPS extractions of the dewatered sludge were analysed for the total organic carbon (TOC), proteins, polysaccharides and humic substances. TOC was measured by a TOC analyser (TOC-5000A, Shimadzu) using the combustion-infrared method. COD and SS were measured according to the Standard Methods [19]. The proteins and humic acids (HA) were determined by a UV/VIS spectrophotometer (Lambda 25, Perkin Elmer) following the modified Lowry method [20] using albumin bovine (Sigma) and humic acid (Fluka) as the standards,

respectively. The polysaccharide content was measured according to the phenol method [21] using glucose as the standard.

Attention was specially paid to the non-filterable organic matter in the sludge centrates. The apparently soluble but non-filterable organic matter in the centrate was collected by filtration with a 0.4-μm polycarbonate membrane filter (Osmonics). The filterate was collected for analysis of its TOC, polysaccharide, protein and humic contents. For an organic parameter, the ratio of its concentration in the filterate to that in the original sludge centrate gave its penetration ratio, *P*. The fraction of the organic content retained on the membrane filter was then calculated from *1-P*, which was termed as the cut-off ratio of the organic by the filter. The organic matter on the filter was analysed using the alcian blue staining method of Passow and Alldredge [22]. Alcian blue is a dye that mainly stains the acidic components of polysaccharides, and was used in this study to indicate the presence of biopolymers. Briefly, an aliquot (0.5 - 5 mL) of the centrate liquor was filtered onto the membrane filter at a low and constant vacuum (30 kPa). The organic material on the filter was stained with 500 μl of 0.02% pre-filtered aqueous solution of alcian blue (8GX, Aldrich) in 0.06% acetic acid (pH 2.5) for two seconds. After staining, the filter was rinsed once with DI water to remove any excess dye and then transferred into 6 ml of 80% H_2SO_4. The filter was soaked for six hours to dissolve the coloured complex of alcian blue-polysaccharides. The absorption of the solution at 787 nm was measured by spectrophotometer, and the polysaccharide content was calculated as the equivalent concentration of xanthan (Aldrich), which is used as the standard for non-filterable particulate polysaccharides. In addition to the chemical analysis, the non-filterable organic matter that was deposited on the filter was observed under a scanning electronic microscope (SEM) (360, Cambridge Stereoscan) following the sample pretreatment detailed by Diao et al. [23].

3. Results and Discussion

3.1. Sludge cake formation and its specific resistance to filtration

SMBR membrane fouling was indicated by the increase in the TMP during the treatment operation. Both the pore fouling and sludge cake resistances increased with water production. The fouling development was affected by the biomass characteristics and the process variables, such as filtration flux, sludge concentration and aeration intensity. When filtration was resumed after a physical wash to remove the sludge on the membrane surface, pore fouling was predominant and sludge cake coverage was less important. However, an increase in the MBR water production brought about continuous sludge deposition on the membrane. The sludge cake accumulation on the membrane surface resulted in a faster increase in the cake fouling resistance than the pore fouling resistance (Fig. 1). The sludge cake fouling component increasingly dominant, which eventually led to serious membrane fouling. In all cases, sludge cake deposition on the membrane surface was shown to be the main cause of the severe membrane fouling. For a low filtration flux of 0.3 $m^3/m^2 \cdot d$ and an aeration intensity of 10 $L/m^2 \cdot s$ through the cross-section area of the reactor, the membrane became severely fouled after about 12 days. The overall sludge cake resistance as estimated in the late phase of the MBR operation was greater than 5×10^{13} 1/m when the TMP increased to 500 mm Hg or higher. Given an estimation of the average cake thickness of 0.5 mm from the mass of sludge cake collected from the membrane, the filtration resistance of the sludge cake was estimated to be around 3×10^{14} m/kg according to Eq. (5).

The specific filtration resistances were determined more accurately by the filterability tests for both the bulk MBR sludge and the cake sludge removed from the membrane (Fig. 2). On average, the bulk sludge of the MBR suspension had a specific resistance of 1.9×10^{11} m/kg (Fig. 3). This was more than three orders of magnitude lower than the resistance of the

sludge cake layer that was attached to the membrane. The mixed liquor of the bulk sludge was separated by sedimentation into settled sludge and supernatant. If the settled sludge had its supernatant replaced by water it was found to have a filtration resistance of 1.9×10^{11} m/kg, which is practically the same value as that of the bulk sludge (Fig. 3). The supernatant of the bulk sludge had a lower specific filtration resistance than both the original bulk sludge and the settled sludge. This result is similar to the previous experimental finding that the contribution of the supernatant to the total resistance of the bulk sludge is not important [24].

The cake sludge that was removed from the membrane had a much lower filterability than the MBR bulk sludge. The specific resistance of the cake sludge in a suspension was about 4.9×10^{13} m/kg. Although the sludge cake formed on the membrane surface from the deposition of the biomass sludge in the reactor, the resistance of the cake sludge was more than two orders of magnitude greater than that of the MBR bulk sludge. The suspension of the cake sludge was also separated by sedimentation into settled cake sludge and its supernatant. Unlike the filterability test for the bulk sludge, the cake sludge had a filtration resistance of 8.4×10^{12} m/kg when its supernatant was replaced by water, which is much lower than the resistance of the original cake sludge. However, the supernatant of the cake sludge suspension had a specific filtration resistance of 5.2×10^{13}m/kg, which is even higher than the value of the cake sludge suspension (Fig. 3). This suggests that the materials in the cake sludge supernatant contributed significantly to the unusually high resistance of the sludge cake formed on the membrane in the SMBR. In other words, the substance that was released from the cake sludge and remained in its supernatant after sedimentation appeared to be largely responsible for the high filtration resistance of the sludge cake attached to the membrane surface during the MBR operation.

3.2. Compositions of the organics in the supernatant and the EPS of the bulk sludge and cake sludge

The EPS contents of the bulk sludge and the cake sludge were rather similar. The bulk sludge had an average EPS of 20.7 mg TOC/g-SS and the cake sludge had an average EPS of 20.6 mg TOC/g-SS (Fig. 4). Compared to the bulk sludge, the cake sludge had slightly more polysaccharides and less proteins and humic acids. Generally speaking, there was little difference between the cake sludge and the bulk sludge in terms of the extracellular property of the biomass. This is consistent with the fact that the bulk sludge in the MBR suspension was the source of the cake sludge on the membrane inside the reactor.

The main difference between the cake sludge and the bulk sludge was found in the liquid phase of the sludge suspensions. The centrate of the bulk sludge had a low organic residue with an average TOC of 3.8 mg/g-SS. However, the centrate of the cake sludge had an average TOC of more than 15.1 mg/g-SS. Despite a certain degree of data variation, the biomass-based concentrations of the polysaccharides, proteins and humic substances in the CS centrate were about three times greater than the values for the BS centrate (Fig. 4). Compared to the MBR bulk sludge, the cake sludge had more organic materials that were associated with the biomass. These organic substances were not microbial EPS, but were trapped in the sludge cake and could be readily released by stirring the sludge cake into a suspension.

Most of the organic matter that remained in the centrate of the bulk sludge was soluble material, or soluble microbial products (SMP), which is what would be expected for an activated sludge suspension. Around 90% of the organic matter in the BS centrate could not be retained by the 0.4-μm filters (Fig. 5). About 20% of polysaccharides (PS) and proteins were retained by the filter, whereas for the humic acids the fraction retained was subject to a larger error because of the low concentration values of about 0.4 mg/g-SS. In

contrast, the major portion of the organic remained in the centrate of the cake sludge after centrifugation was not SMP but rather non-filterable substances. Nearly 70% of the organic matter in the CS centrate was intercepted by the 0.4-μm filters (Fig. 5). For the polysaccharides and proteins, the ratio of interception by the filters was also about 70%, whereas for humic substances the cut-off fraction was more than 80%. The results suggest that most of the organic materials that remained in the centrate liquor of the cake sludge were apparently larger than 0.4-μm. They were not in the form of SMP, but were probably large organic polymers or biopolymer clusters (BPC). The amount of non-filterable BPC as measured by the TOC in the sludge centrate was 10.3 mg/g-SS for the resuspended cake sludge and 0.4 mg/g-SS for the bulk sludge.

The non-filterable BPC that remained in the sludge centrates were further identified by the alcian blue staining method. Alcian blue binds with the acidic components of particulate polysaccharides. Of the 3.8 mg/g-SS of TOC in the centrate of the MBR bulk sludge, about 1.0 mg/g-SS that was collected by the filter and stained by alcian blue can be regarded as particulate polysaccharides in xanthan equivalent. Of the 15.1 mg/g-SS of TOC in the centrate of the cake sludge suspension, around 9.4 mg/g-SS that was collected by filtration and stained by alcian blue behaved like particulate polysaccharides in xanthan equivalent. Although polysaccharides made up only a fraction of the organic material in the sludge centrate, they gave an important indication of the presence of organic polymers, including polysaccharides, proteins and humic and other substances.

The biopolymer clusters collected onto the 0.4-μm membrane filter from the sludge centrates were examined with SEM micrographs. The materials that remained in the centrate of the cake sludge formed an apparent slime layer with a few microbial cells on the filter (Fig. 6a). These organic materials were not sludge flocs, but rather biopolymer clusters of proteins, polysaccharides and other organic substances. In contrast, in the MBR bulk sludge centrate,

apart from a few cells, no apparent organic matter in solid form was retained on the filter (Fig. 6b). The SEM observation provides further evidence that the large BPC found in the centrate of the cake sludge suspension were the main foulants in the sludge cake, and were the cause of the serious increase in TMP during the MBR treatment process.

3.3. Fouling characteristics of the sludge cake formed on the membrane

This study shows that the cake sludge attached to the membrane surface in an MBR contains a considerable amount of organic materials. These organic substances, which can be readily removed from the cake sludge, are neither microbial cells nor SMP, but biopolymer clusters. The formation and accumulation of BPC in sludge cake are mostly responsible for the high filtration resistance of the cake sludge found in this test and other studies [24,25]. During MBR filtration, a sludge layer will inevitably be deposited on the membrane surface because of sludge interception [1,9,13]. Nonetheless, the sludge cake formed by sludge flocs should have a porous structure with a modest filtration resistance, as determined by the present filterability test for the MBR bulk sludge (Fig. 3). The BPC will be retained by the sludge layer, accumulate and fill up the pores within the sludge cake. Meanwhile, a portion of the SMP in the MBR suspension that penetrates with the permeate through the sludge layer will also be trapped by the sludge to form large-sized BPC. Previous investigations have shown that the MBR effluent has a lower organic concentration than that of the supernatant of the bulk sludge [2,26,27]. This lower concentration of organic material in the effluent is probably caused by the adsorption and interception of SMP and other organic macromolecules by the sludge layer on the membrane.

BPC may be viewed as a special form of organic matter revealed by the present study in the SMBR system. They are apparently formed by the affinity clustering of free EPS and SMP in the sludge cake deposited on the membrane surface. The increase in both the quantity

and size of biopolymers in the sludge cake greatly increases the filtration resistance and TMP of the MBR membrane. In other words, the accumulation of biopolymers causes severe pore fouling in the sludge cake layer. As a result, the interaction of the biomass flocs and the biopolymers builds up a sludge cake with a filtration resistance that is much higher than expected for bulk activated sludge in the MBR suspension, and the membrane is severely fouled by even a thin layer of sludge cake. Nonetheless, this type of membrane fouling is reversible. The sludge cake can be readily removed by physical cleaning with water flushing, and the filterability of the membrane can be largely recovered [2,28,29].

4. Conclusion

Sludge cake formation is the main cause of severe membrane fouling in the SMBR process used in biological wastewater treatment. The sludge cake attached to the membrane that was used in this SMBR study had a high specific filtration resistance of the order of 10^{14} m/kg. Little difference was found between the cake sludge that was removed from the fouled membrane and the bulk sludge of the SMBR suspension. However, the results of the filterability tests show that the cake sludge had an average filtration resistance of 4.9×10^{13} m/kg, whereas the dewatered sludge cake formed by the simple filtration of the bulk sludge had an average filtration resistance of only 1.9×10^{11} m/kg. A pool of biopolymer clusters that was trapped within the sludge cake on the membrane during the MBR operation was discovered. These biopolymer clusters could be readily separated from the cake sludge by stirring into a suspension, and were neither microbial mass nor EPS nor SMP. The non-filterable BPC as measured by the TOC was about 10.3 mg/g-SS for the cake sludge compared to 0.4 mg/g-SS for the bulk sludge. The organic components that were collected from the cake sludge supernatant had an average specific filtration resistance of 5.2×10^{13} m/kg. SEM examination revealed that the BPC materials readily formed a slime layer on a

0.4-μm filter. With the BPC removed, the cake sludge had its filtration resistance largely reduced to 8.4×10^{12} m/kg. It is argued that BPC are a special form of the organic materials formed by affinity clustering of free EPS and/or SMP in the sludge cake on the membrane surface. The accumulation of the BPC within the pores of the sludge cake was mostly responsible for the high filtration resistance of the cake sludge. The interaction of the biomass flocs and the BPC built up a sludge cake with an unusually high filtration resistance, which resulted in serious membrane fouling in the SMBR treatment process.

Acknowledgements

This research was supported by grants HKU7114/04E and N-HKU737/04 from the Research Grants Council (RGC) of the Hong Kong SAR Government and funding from the Outstanding Young Researcher Award of the University of Hong Kong. The technical assistance of Mr. Keith C. H. Wong is highly appreciated.

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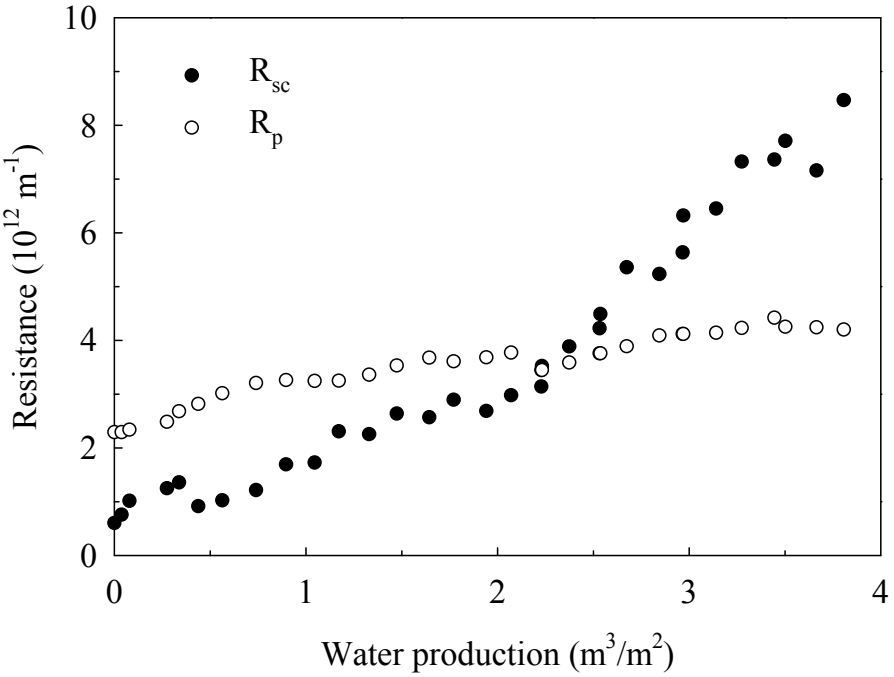

Fig. 1. Sludge cake resistance and pore fouling resistance determined for a typical test run of the SMBR with a sludge concentration of 6 g SS/L, an effluent flux of 0.3 $m^3/m^2 \cdot d$ and an aeration intensity of 10 $L/m^2 \cdot s$.

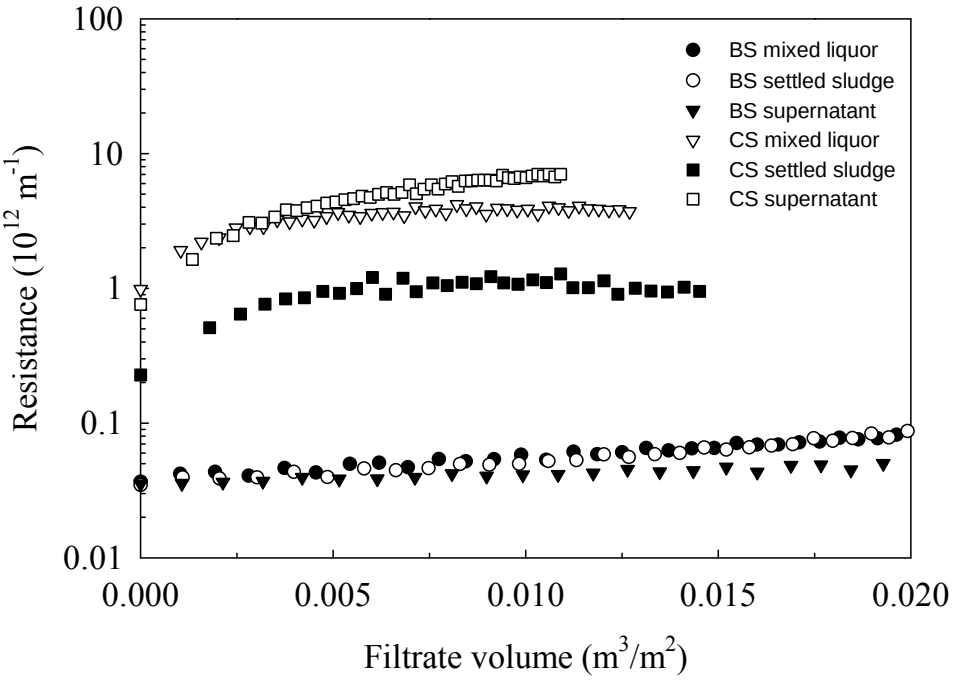

Fig. 2. Comparison of the bulk sludge and the resuspended cake sludge for the filterability of the mixed sludge liquor and its settled sludge and supernatant.

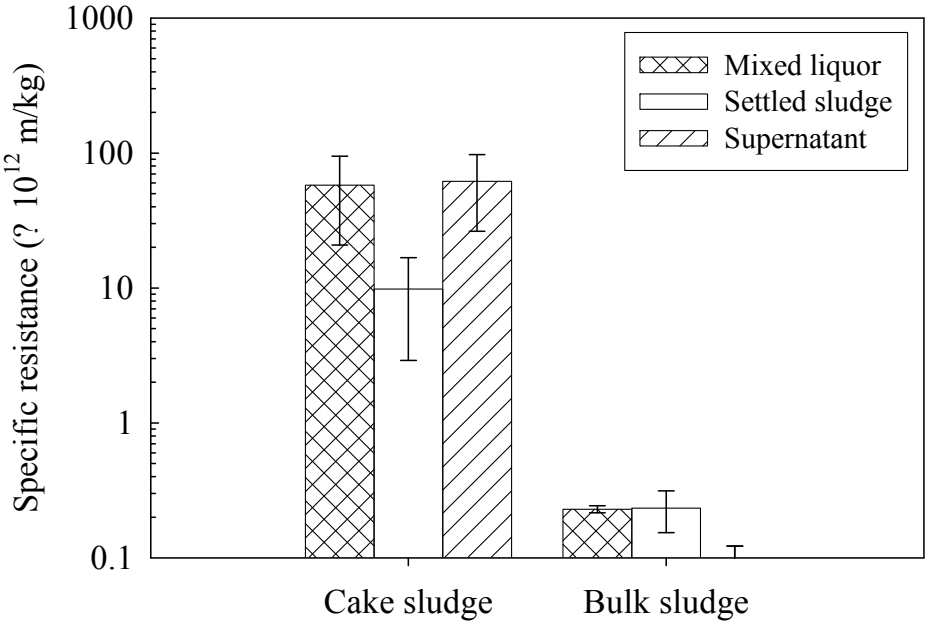

Fig. 3. Specific resistances of the cake sludge that was removed from the membrane and the bulk sludge of the SMBR suspension.

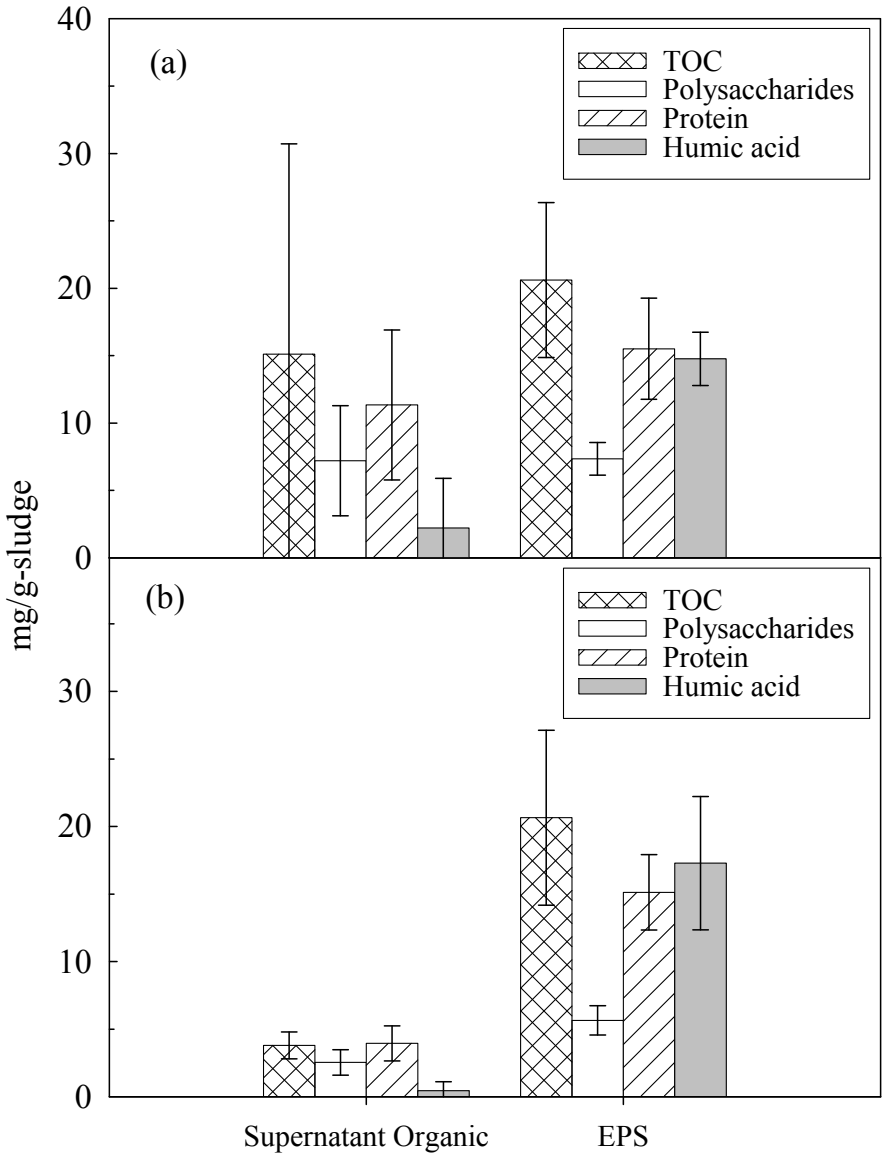

Fig. 4. Organic materials and their composition in the supernatant and the EPS of (a) the cake sludge removed from membrane and (b) the bulk sludge of the SMBR suspension.

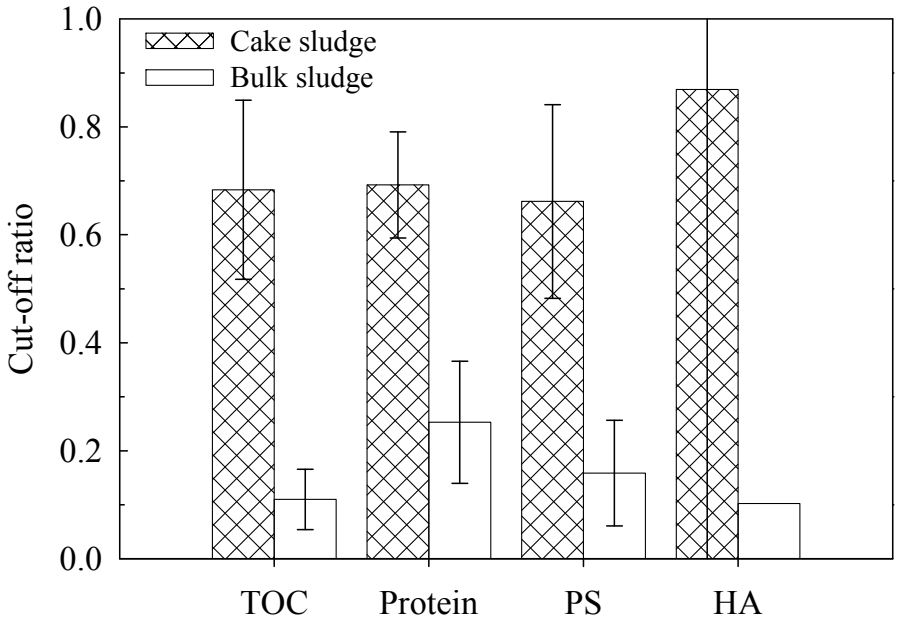

Fig. 5. Cut-off ratios by the 0.4-μm filter for the organic materials and their components in the supernatants of the bulk sludge and the resuspended cake sludge.

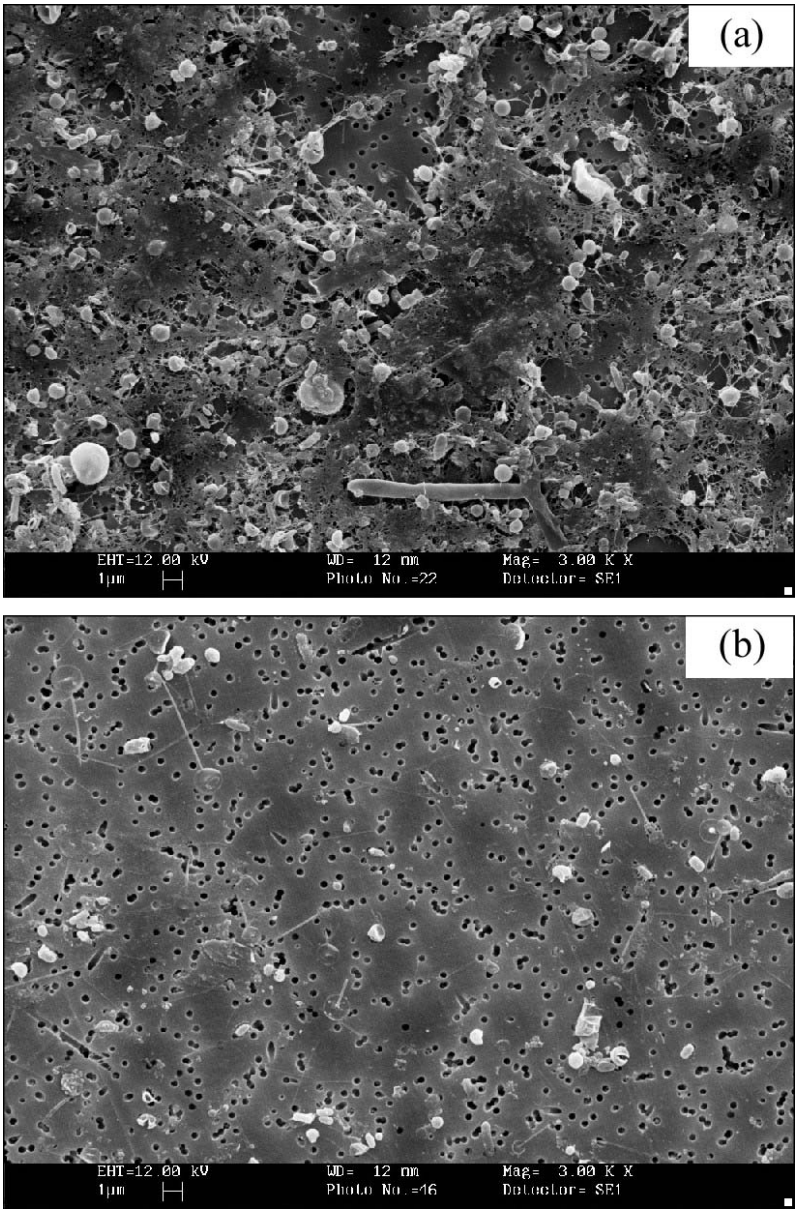

Fig. 6. SEM micrographs of the organic materials that were retained on the filters from the supernatants of (a) the resuspended cake sludge and (b) the bulk sludge.