

Ragging phenomenon characterisation and impact in a full-scale MBR

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ABSTRACT

Although there are few studies about clogging phenomenon in the peer-reviewed literature, it is considered one of the main operational challenges by membrane bioreactor (MBR) practitioners. This study presents data from the performance of a full-scale MBR affected by clogging, and ragging in particular. An evaluation of the efficiencies of different applied cleaning methods revealed the acid recovery cleaning to be more efficient than the basic recovery cleanings, although all maintenance cleanings were largely ineffective in recovering membrane permeability. Only declogging cleaning through the manual removal of the accumulated solids was found to be efficient, indicating that such solids were substantially unremoved by chemical cleaning. Moreover, reclogging following manual cleaning demonstrated a propensity for rapid clogging – within a period of 10 days over which the permeability returned to 68 and 88% of the pre-cleaned state. The analysis of the feedwater indicated suspended textile fibres (>70% cotton) to be present at a concentration of more than 40 mg·L⁻¹, ~90% being smaller than 1 mm (0.06–0.4 mm). These small lengths of filaments evidently pass through pre-treatment and are retained on the membrane surface, forming ‘rags’ within the membrane module, notwithstanding the routine high quality of sludge reflected in the capillary suction time and filterability measurements. Pre-treatment improvement, manual cleaning and permeate flux reduction are the only options to minimise ragging impact over MBR performance.

Key words | fibres, full-scale, membrane bioreactor, municipal wastewater, ragging

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INTRODUCTION

Membrane bioreactors (MBRs) combine activated sludge treatment with membrane filtration to provide a number of widely acknowledged advantages over conventional activated sludge treatment. These include a smaller footprint, due to the elimination of secondary settlers, the possibility of working with high mixed liquor suspended solids concentrations, limited sludge production and a high effluent quality with high nutrient removal efficiencies (Judd 2011). However, the technology is constrained by the tendency for the membrane permeability to decrease, demanding periodic physical and chemical cleaning which then increases operating and capital costs, the latter through the requirement for extensive pre-treatments (Frechen *et al.* 2008).

Although most of the scientific articles about MBR systems suggest membrane surface fouling as being the main operational limitation for the filtration component and

impact of different operation conditions on membrane fouling and extracellular polymeric substances (EPS) production (Dvořák *et al.* 2011), recent studies of full-scale MBR operation have shown that the clogging phenomenon and inefficient pre-treatment are of primary concern to the practitioner community (Santos *et al.* 2011), and that clogging is measurable both at pilot (Zsirai *et al.* 2012) and full scale (Mason *et al.* 2010; Stefanski *et al.* 2011). Clogging arises when agglomeration of solids takes place within or at the entrance to the membrane channels, affecting the permeability of the filtration process (Judd 2011). Clogging can be categorised as ‘sludging’ or ‘ragging’. Sludging refers to the filling of membrane channels with sludge solids and depends on process design (membrane module and aerator, pre-treatment), flux and flux distribution, and membrane aeration distribution (Lebogue *et al.* 2009; Zsirai *et al.*

2012). Ragging (or 'braiding') is the term used to define the blocking of membrane channels with particles agglomerated as long rag-like particles (Mason *et al.* 2010; Judd 2011). It is more relevant in municipal wastewater treatment plants, since the rags are primarily made up of cellulosic fibres and hairs (Frechen *et al.* 2008; Schier *et al.* 2009; Stefanski *et al.* 2011), possibly relating to the disposal of cotton wool-based products to sewer (Stefanski *et al.* 2011).

Sludge quality strongly depends on feed sewage characteristics, and it has been assumed by most practitioners that the clogging propensity relates primarily to the level of pre-treatment applied (Itokawa *et al.* 2008; Lesjean *et al.* 2009; Brepols *et al.* 2010). However, the most recent evidence suggests that agglomeration into rags takes place within the treatment process, notwithstanding the rigour of the upstream screening step, and that ragging propensity can be estimated from the coarse suspended solids (CSS) concentration, defined as those solids retained by a mesh of ~2 mm (Stefanski *et al.* 2011). Since there have been no other published analyses of rags (the report by Stefanski *et al.* (2011) contained purely physical analyses), it is unclear as to whether cotton wool is the exclusive cause of rag formation.

This paper aims to provide further insight into the ragging phenomena in MBRs through the identification of (a) the impact of ragging on MBR permeability, (b) the most appropriate cleaning method for the removal of rags, and

(c) the composition and characterisation of ragging substances. This study was conducted on a full-scale immersed MBR visibly affected by ragging.

METHODS

Wastewater treatment facility

A full-scale MBR facility treating municipal wastewater and located in the north-east of Spain was evaluated. This wastewater treatment plant (WWTP) has a hybrid configuration comprising pre-treatment based on coarse screen (8 cm), grit chamber, buffering (1,110 m³), fine screening (1 mm), a carousel bioreactor and two MBR tanks (A and B), with classical sedimentation employed during peak flows (Brepols *et al.* 2008). The facility treats a maximum daily flow of 3,225 m³·day⁻¹ by membrane ultrafiltration and the possible overflow through the settling process.

A detailed description of the MBR and the cleaning methods applied are presented in Table 1. The effluent flow-rate and the trans-membrane pressure were respectively monitored by a flowmeter and a pressure gauge, and data were stored in a supervisory control and data acquisition system (SCADA).

Table 1 | Full-scale MBR characteristics and cleaning methods applied (SAD_m: Specific aeration demand with respect to membrane area)

Volume of each membranes tank	m ³	30
Manufacturer, membrane model		Zenon, 500c
Membrane material, configuration		PTFE, Hollow fibre
Fibre length, pore diameter	mm, µm	1,900; 0.04
Total membrane area (both tanks)	m ²	5,808
SAD _m	Nm ³ ·m ⁻² ·h ⁻¹	0.405
Filtration cycle		10 min filtration/40 sec backpulse (adding ≈6.3 mg·L ⁻¹ of NaClO)
Average flux	LMH	27 ± 1
Type of cleanings:		
Maintenance cleaning (MC)		Backwashing with a solution of 140 mg·L ⁻¹ of NaClO and 200 mg·L ⁻¹ of EDTA for 45 min
Recovery cleaning (RC)		Backwashing with a basic or acid solution and soaking the membranes in this solution for 6–12 h.
Basic recovery cleaning (bRC)		RC using a NaClO (hypochlorite sodium) solution of 1,500 mg·L ⁻¹
Acid recovery cleaning (aRC)		RC using a C ₆ H ₈ O ₇ (citric acid) solution of 1,500 mg·L ⁻¹
Declogging (manually) (DC)		Removing membranes from the tank and cleaning them manually by removing the solids adhered to the membrane

LMH: L m² h⁻¹.

Sampling and analytical methods

Sludge samples from the membrane tanks were taken from sample points in the recirculation pipework. Influent samples were taken downstream of the fine-screen.

Concentrations of mixed liquor suspended solids and mixed liquor volatile suspended solids (MLSS and MLVSS, respectively) were determined according to the APHA (2005) standard methods 2540D and 254 °C. Sludge volume index (SVI) was determined according to Metcalf and Eddy (2003). The dewaterability of the different mixed liquor samples was evaluated by the capillary suction time (CST, Triton Electronics Ltd, type 304 B). Filterability was determined using the protocol described by Kubota® through filtration of 50 mL of sample through a 2–4 µm pore disc filter (ALPL1244185) under gravity. Each CST and filterability measurement was performed at least three times until a standard deviation of less than 5% was attained from triplicate measurements. The particle size distribution (PSD) was measured with a particle size analyser (Beckman Coulter LS 13 320) using the Universal Liquid Module and including the PIDS (polarization intensity differential scattering) to measure the small particles.

Filtered supernatant was analysed for soluble microbial product. Extraction of bound EPS from the sludge samples was through the cationic exchange resin method of Frøelund *et al.* (1996). Protein concentration was measured spectrophotometrically using Lowry method (Lowry *et al.* 1951) as modified by Peterson (1979). Polysaccharides content was analysed using Dubois method (Dubois *et al.* 1956) using a 5% phenol concentration (Raunkjaer *et al.* 1994).

Both sludge and influent CSS concentration measurement was carried out according to Stefanski *et al.* (2011) using mesh sizes of 0.063, 0.4, 1, 1.5, 2, 4 and 5 mm. The coarse solids reconstitution test was also applied for all the solids retained in all the meshes used.

Influent textile fibres identification and characterisation was conducted by applying the standard methodology described by UNE-EN-ISO regulation (AENOR 2011). These determinations were based on the quantitative analysis of each fibre's typology (protein, polyamide, cotton, acrylic and polyester) using different solvents (hypochlorite sodium, formic acid, sulphuric acid and dimethylformamide) and microscopic analysis. The fibres content of the sludge adhered on the membranes was determined by microscopic analysis using a Nikon eclipse E200 microscope and contrast-phase determinations (Ford & Roff 1954; Greaves 1995).

Permeability recovery calculation

The permeability recovery has been calculated by Zsirai *et al.* (2012) as:

$$\text{Permeability recovery} = \frac{L_c - L_{\text{end}}}{L_{\text{start}} - L_{\text{end}}} \times 100$$

where L_c is the permeability immediately after cleaning, L_{end} the permeability at the end of the previous test recorded immediately before the clean, and L_{start} the permeability after the cleaning of the previous test. The permeability recovery can be higher than 100% when calculated this way due to the possibility of increase in the efficiency of the latest cleaning, obtaining lower values for the permeability than the one used at the beginning.

RESULTS AND DISCUSSION

Permeability evaluation

The evolution of permeability for both MBR tanks (A and B) is represented in Figure 1. Permeability values (K) were extremely low at below 60 LMH·bar⁻¹, generally considered unsustainable for MBR operation (Judd 2011). Fourteen and 16 chemical cleans were applied to the tanks A and B respectively during the period from 120 to 270 or 280 days prior to manual cleaning. Cleans comprised 10 maintenance and four recovery cleanings for Tank A and 12 maintenance and four recovery cleanings for Tank B. All the maintenance cleanings (MC) employed sodium hypochlorite (140 mg·L⁻¹) and ethylenediaminetetraacetic acid (EDTA: 200 mg·L⁻¹). Three of the four recovery cleanings were basic (bRC) using 1.5 g·L⁻¹ sodium hypochlorite while the other one was an acid recovery cleaning (aRC) of 1.5 g·L⁻¹ citric acid. Mean permeability recoveries obtained from each type of cleaning prior to the 'declogging' cleaning (DC), the manual removal of accumulated solids, are shown in Figure 2.

Recovery cleanings were found to be at least twice as efficient as MC, and aRC was more efficient than the bRCs (as expected because textile fibres are soluble at low pH). However, recovered permeability values were insignificant compared to those obtained by DC, indicating chemical cleaning to be largely ineffective at removing gross accumulated solids associated with 'sludging'.

Whilst DC provided a significant permeability recovery, after 10 days of operation the permeability values dropped

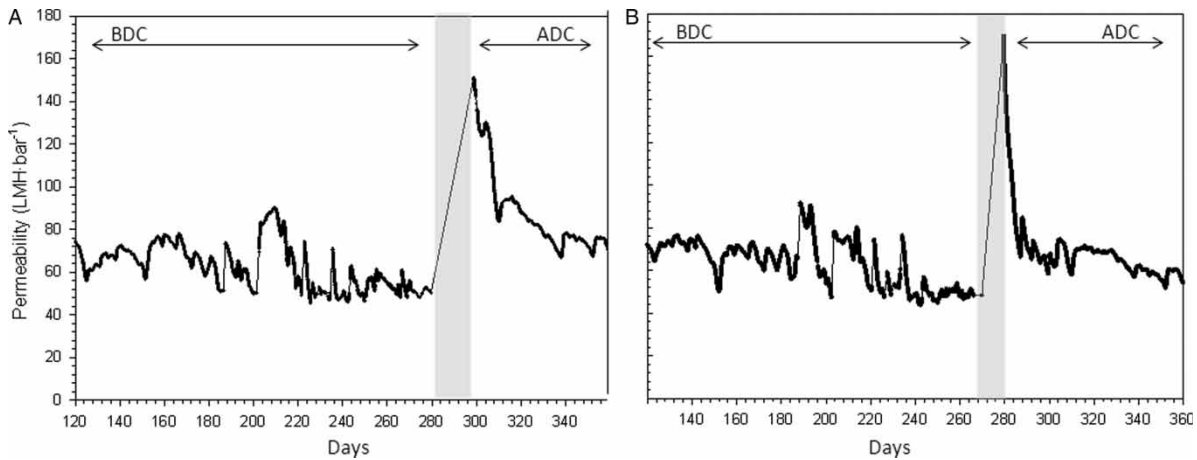


Figure 1 | Permeability values of each tank during 2011: A, permeability tank A; B, permeability tank B. BDC: Before Declogging Cleaning, ADC: After Declogging Cleaning.

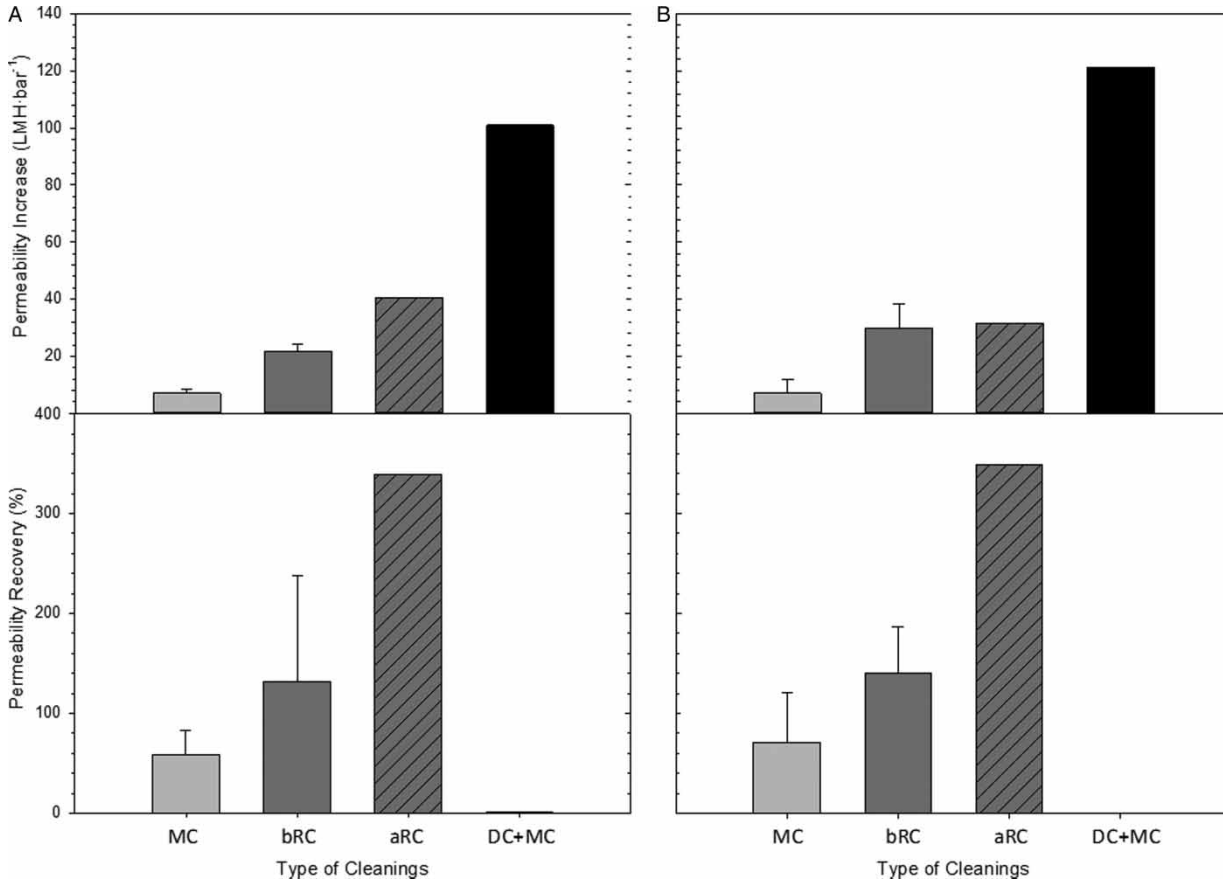


Figure 2 | Average permeability recoveries and permeability increases after each chemical cleaning applied. It was not possible to calculate the permeability recovery for the declogging cleanings.

by 68–88% of the cleaned state. During the 2 month period following the DC, five and seven maintenance cleanings were applied again to Tanks A and B respectively. Whilst the maintenance cleanings applied after the DC were

slightly more efficient than the ones applied before (BDC: 7 ± 3 LMH·bar⁻¹, ADC: 10 ± 5 LMH·bar⁻¹), this improvement was insignificant compared to the overall loss of permeability from ‘relogging’ – the accumulation of solids

following the DC. Evaluated permeability trends (dK/dt) between all chemical cleans revealed permeability decline to be greater when clogging was more pronounced (Figure 3). Pearson coefficient test showed no correlation between permeability decline values (dK/dt , $\text{LMH}\cdot\text{bar}^{-1}\cdot\text{day}^{-1}$) and recovery permeability. These results corroborate recent reports of rapid clogging from pilot-scale studies (Zsirai *et al.* 2012).

Nowadays, to maintain a sustainable operation and minimise cleaning frequency at the full-scale facility affected by ragging, the permeate flux is slightly reduced (from 27 to 24 LMH).

Sludge characterisation

Visual inspection of the membrane modules conducted prior to manual cleaning revealed significant clogging at the top of the membrane cassettes (Figure 4) with a highly

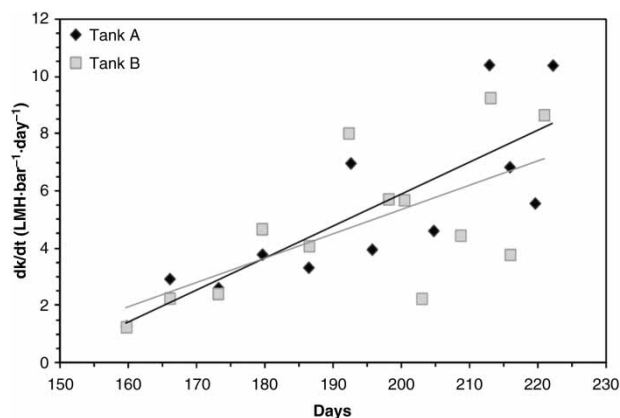


Figure 3 | dK/dt after each chemical cleaning applied before the DC.

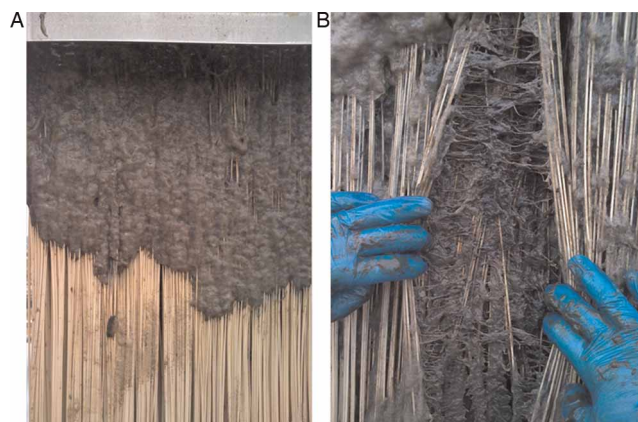


Figure 4 | Pictures of the ragged membranes. A, Top of the cassette. B, Inside the cassette.

adherent ‘slimy’ material filling the membrane interstices and severely restricting their physical movement. The sludge sampled from the membrane tank revealed little significant change in the key bulk properties of MLSS, MLVSS, SVI, CST, PSD and filterability throughout the study (Table 2), with the low CST and SVI values indicating good sludge quality (Khongnakorn & Wisniewski 2010; Lousada-Ferreira *et al.* 2010). Likewise, there were no foaming episodes during the study.

A qualitative ‘ragging propensity’ test (Stefanski *et al.* 2011) was applied to the sludge adhered to the membranes through successive CSS fractionation (5 mm down to 63 μm). The test demonstrated reconstitution of the suspended solids as rags, which were self-supporting when suspended. The rags were around 50 mm in length for the solids retained in the smallest mesh size (0.063 mm), up to 70–120 mm for the solids taken from the larger mesh size ranges (0.4–2 mm). No rags were observed for the largest mesh sizes of 4 and 5 mm. The mechanical integrity of the reconstituted rags was unaffected by the application of either detergent or hypochlorite, corroborating the reports of Stefanski *et al.* (2011). This measurement gives an idea of the pre-treatment requirement to minimise the ragging phenomenon in MBR facilities.

Textile fibre concentration and characterisation

The WWTP influent was analysed to determine the quantity and structure of textile fibres and cellulosic material possibly affecting filtration performance. Samples from the WWTP entrance were screened at different screen ratings. The mean fibre concentration in the influent

Table 2 | MBR sludge properties

Parameter	Units	Average (all studied period)
MLSS	$\text{mg}\cdot\text{L}^{-1}$	$6,000 \pm 1,400$
MLVSS	%	78 ± 3
SVI	mL	290 ± 90
Filterability	mL	30 ± 3
CST	sec.	62 ± 10
EPS	$\text{mg}\cdot\text{g VSS}^{-1}$	13 ± 3
Soluble proteins	$\text{mg}\cdot\text{g VSS}^{-1}$	2.7 ± 0.8
Soluble polysaccharides	$\text{mg}\cdot\text{g VSS}^{-1}$	3.7 ± 0.6
Bound proteins	$\text{mg}\cdot\text{g VSS}^{-1}$	3.5 ± 1.2
Bound polysaccharides	$\text{mg}\cdot\text{g VSS}^{-1}$	3.4 ± 1.5
PSD (% volume)	μm	77 ± 10

was $42 \pm 21 \text{ mg}\cdot\text{L}^{-1}$, mostly below 1 mm in size: 38% 0.06–0.4 mm, 52% 0.4–1 mm, 10% 1–2 mm. Characterisation of the fibre material revealed them to be primarily cotton and cellulosic in origin (73%), with protein-based materials such as wool and other animal hairs (22%) making up much of the remainder along with small amounts of polyamides (3%), and polyester (2%). Furthermore, optical microscopic analysis of the agglomerated rags revealed them to comprise primarily cotton fibres, in keeping with the observations of Stefanski *et al.* (2011), who also identified cotton-based filaments as being the root cause of ragging in MBRs.

CONCLUSIONS

The performance of a full-scale MBR affected by ragging, the agglomeration of small textile filaments into long rags or braids, has been investigated. Ragging was demonstrated using a previously published qualitative empirical test, and was identified as being the cause of significant permeability decline which remained largely unaffected by the routine maintenance chemical cleans applied. Whilst declogging, the manual removal of accumulated solids, provided a significant permeability recovery, after 10 days of operation the permeability values returned to 68–88% of the pre-cleaned state. Ragging was thus demonstrated as being significant and rapid for this installation, and to be unmitigated by the action of either chemical cleaning or backwashing.

Examination of the solids accumulated within the MBR membrane fibres revealed them to form self supporting rags of 70–120 mm in length. Optical analysis of these fibres indicated that they were formed primarily of cotton filaments. Analysis of the MBR plant influent revealed the presence of textile fibres at an average concentration of $40 \pm 20 \text{ mg}\cdot\text{L}^{-1}$, also primarily composed of cotton (>70%). The short length of these fibres (<1 mm) evidently allows them to pass through the pre-treatment stage, including fine screening to 1 mm, and agglomerate as rags within the membrane. The empirical test revealed the clogging solids to form mechanically stable 70–120 mm long rags when suspended in air.

It was concluded that ragging by cotton filaments presents a serious challenge to MBR operation, notwithstanding the application of a fine screen upstream of the process and the low values of the classical bulk sludge filterability determinants such as capillary suction time. Although ragging is relatively easy to detect, it is almost impossible to solve, and pre-treatment improvement,

manual cleaning and permeate flux reduction are the only options to minimise ragging impact over MBR performance.

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