A real trial of a long-term non-fouling membrane bioreactor for saline sewage treatment
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ABSTRACT
This paper reports on a pilot trial of a novel MBR developed with coarse-pore membrane module by the authors. The plant was operated for 370 days with up to 7 m$^3$/d raw saline sewage after 3-mm screening. The plant performed successfully without membrane fouling for 270 days except an accidental power source failure for 30 h, during which membrane was fouled under no aeration and mixing condition. EPS increases in both the reactor and the bio-cake on the membrane surface explained this fouling. The average TSS, COD and TKN removal efficiency were 92, 90, and 93%, respectively, under a high effective permeate flux of 4.8 m/d and a low air-to-water ratio of 15.

Key words | coarse-pore membrane bioreactor, extra-cellular polymeric substance (EPS), membrane fouling, saline sewage, real trial

INTRODUCTION
In recent years, membrane separation technology combined with biological nutrient removal (BNR) processes has been widely used in both municipal and industrial wastewater treatment. Compared with conventional activated sludge process, the membrane bioreactor (MBR) has many advantages such as small footprint, reduction of sludge production, and good effluent quality (Miura et al. 2007). With the size of the installations growing rapidly (Kanai et al. 2007), more and more operation problems have been exposed, such as frequent membrane fouling (Brannock et al. 2010), low permeate flux (0.2–1 m/day) (Melin et al. 2006) and high operation energy cost (Zhang et al. 2003). These all restrict the widespread application of MBR in domestic wastewater treatment due to high operation and maintenance (O&M) costs (Miura et al. 2007). Moreover, intensive membrane fouling of current micro-filtration-membrane MBR in treatment of saline sewage was observed (Tam et al. 2006). Seawater was used to flush toilets in Hong Kong, which resulted in saline sewage containing 2,800 mg/L chloride on average. In order to solve these problems, a novel MBR has recently been developed using coarse-pore membrane modules (Bai et al. 2010, patented already). A pilot-scale trial of up to 7 m$^3$/day saline sewage has been conducted for more than a year in Hong Kong. More than 370 days operation without membrane fouling was achieved, except that an accidental failure of power source happened on day 270, which caused a sharp increase in trans-membrane pressure (TMP) from 0.2 to 0.6 bars under a non-aeration condition for more than 30 h, resulting in the fouling of the membrane.

Many researches have been focused on the pore blocking on the surface of membranes, and the subject is very abstruse and complex. However, it is largely agreed that membrane fouling in MBRs can be attributed primarily to extra-cellular polymeric substance (EPS) (Henze et al. 2008). EPS is a complex mixture of carbohydrates, proteins, humic compounds, uronic acids, and DNA (Frølund et al. 1996). For a submerged MBR, a period of relatively low fouling resistance was followed by a sudden rise in resistance, which was due to an increase in the suspension viscosity caused by levels of EPS in the feed (Nagaoka et al. 1996). Furthermore, a three stage history for membrane fouling in MBRs was proposed for the blocking/fouling process: (i) an initial short-term rapid rise in transmembrane pressure (TMP), (ii) long-term linear or weakly exponential rise in TMP, and (iii) a sharp increase in dTMP/dt, also known as the TMP jump. The supernatant EPS, especially the polysaccharides, are regarded as the
major membrane foulants (Zhang et al. 2006). Therefore, the aim of this study was to reconstruct the pilot plant and investigate the membrane fouling caused by the accidental failure of the power source.

**MATERIALS AND METHODS**

**Pilot-scale MBR**

Figure 1 shows the schematic of the pilot-scale MBR using the coarse-pore membrane. It was equipped with flat-sheet (FS) coarse-pore (> 10 μm) membrane modules having a total surface area of 1.75 m². The raw saline sewage was taken from a sewer in the Hong Kong University of Science and Technology, passing through a 3-mm screen, to the 1.5 m³ bioreactor continuously. The plant consisted of an aerobic and anoxic compartment. The membrane modules were installed in the aerobic compartment. A constant flow permeate was obtained (4 m/d). An effluent tank supplied about 1% of treated water for membrane once per 60 h. The mixed liquor suspended solid (MLSS) concentration and the hydraulic retention time (HRT) in the reactor were maintained at 2,600 mg/L and 5.5 h, respectively. Detailed plant information and operation conditions can be found from our previous study (Bai et al. 2010). The average influent quality is summarised in Table 1.

The average daily inflow rate was up to 7 m³ and the corresponding HRT was 5.5 h. Since the sewer sewage flow varied diurnally, two water level sensors were used to control the water level in both the bioreactor and the equalisation tank so that a constant inflow rate could be maintained according to a tested permeate flux. The MLSS concentration was around 2,600 mg/L. When different membrane fluxes were tested the sludge retention time (SRT) changed correspondingly, which could be determined from the daily escape of SS via the effluent since there was no withdrawal of sludge from the bioreactor. When the flux was tested between 2 and 5 m/day, the SRT was found to be 36 and 172 days, respectively. Different air supply rates from 60 to 72 m³/d were also tested in order to determine the minimum air-to-water ratio. The resulting DO in the aerobic compartment was maintained between 2.2 and 2.8 mg/L, while pH was between 6.5 and 6.9. The water temperature varied from 18 to 30 °C from winter to summer. Backwash was conducted for around 1 minutes per 60 h, using 1% of treated water taken from the effluent tank.

**Analytical method**

EPS was extracted from the re-suspended bio-cake using heat treatment (Morgan et al. 1990). The extract was then measured as polysaccharides which can be extracted from the disinfected water by mixing with a cation exchange resin (CER) (provided by ECUST), followed by determination using anthrone method (Frølund et al. 1996). MLSS, mixed
liquor volatile suspended solids (MLVSS), and suspended solids (SS) were determined according to the Standard Methods (APHA 1998). Colorimetric flow injection analysis (FIA, QuikChem, 8000 FIA +, Lachat) was used to measure ammonium nitrogen (Bromocresol purple method) and nitrite nitrogen (Sulfanilamide method). COD was measured using the HACH method.

For SEM analysis, a panel of the flat-sheet membrane covered with bio-cake layers was taken out from the reactor and a piece of the membrane was cut from the middle of the fouled membrane module. The sample was fixed with 2% (v/v) glutaraldehyde in 0.1 M phosphate buffer at pH 7.2 for 2 h and then washed twice for 10 min and again immersed for 1 h in 0.1 M phosphate buffer. The samples were then fixed with 1% OsO₄ in 0.1 M phosphate buffer for 2 h and washed again in the same way. The fixed sample was dehydrated in an ethanol series (sequentially in 50, 70, 80, 90, and 100% for 15 min each) and substituted with isoamyl acetate (Miura et al. 2007). After that, the fixed samples were coated with aurum–platinum alloy with coating depth 10 nm for 2 min. The coated sample was examined under the SEM with EDX (Jeol JSM6300). The SEM images were taken to determine the morphology of foulants in the bio-cake layers and characterise the bio-cake layer formation on the membrane surface. The elements C, N, O, Mg, Al, S, P, Ca, and Fe were detected using the SEM equipped with EDX spectroscopy.

RESULTS AND DISCUSSION

Figure 2 shows the 24-h composite concentrations of total suspended solids (TSS) and COD in the influent and effluent and their removal efficiencies. The average removal efficiencies of TSS and COD reached 92 and 90%, respectively.

Figure 3 shows the 24-h composite concentrations of ammonium nitrogen and total Kjeldahl nitrogen (TKN) in the influent and effluent and their removal efficiencies. The average removal efficiencies of ammonium nitrogen and TKN were 92 and 93%, respectively. More than 82% of total nitrogen (TN) was removed. Although influent COD and TSS varied daily significantly, the effluent quality was stable, with average COD, SS, NO₃-N, ammonia-N, and TN of 27, 15, 2.7, 1.9, 7.7 mg/L, which fulfilled the secondary effluent discharge standards of Hong Kong. The air flow rate was reduced from 72 to 60 m³/d on day 255, which resulted in a low ratio of air to water at 15.

In the 370 days of operation the pilot plant performed stably. Figure 4 shows that, after each backwash, the TMP returned to 0.1 bars on average. During the whole trial, no chemical cleaning was applied. The first break of the operation was due to holiday, whilst the second was caused by the power source failure during which the TMP suddenly increased from 0.2 to 0.6 bars. The fouled membrane modules were taken out for investigation so that new membrane modules were installed to resume the operation from day 280, though the membrane can be cleaned chemically.

As shown in Figure 4, before the third fouling step, i.e. the sudden TMP jump, our MBR system was operated in the second fouling step for almost seven months, during which the TMP was gradually increased but likely stable at 0.23 bars which is far below the critical TMP of 0.6 bars for causing membrane fouling of this system. At day 270, an accidental power off happened and lasted 30 h, during which neither aeration nor mixing was available in the reactor. During the power failure period, no DO can transfer into the bio-cake on the membrane, thereby accelerating the EPS release. This is because no oxygen can penetrate through 150 μm of this layer (Lewandowski & Beyenal 2004). Bio-cake formation

![Figure 2](https://iwaponline.com/wst/article-pdf/63/7/1519/445643/1519.pdf) | TSS and COD removal.
reduces the permeability, the degree of which depends on variations in EPS generated by aerobic bacteria and released when the bacteria are dying (Zhang et al. 2006). As shown in Figure 5, EPS concentrations in the mixed liquor and in the bio-cake were 17.4 and 23.2 mg/g MLSS, respectively, before the accident, while during the accident the EPS concentration increased to 67.7 and 121.8 mg/g MLSS. This explains our membrane fouling owing to the accumulation of EPS on the membrane. The increase of EPS was further confirmed by increase in the C/N ratio measured by EDX spectroscopy. Obviously, as a primary contributor to membrane fouling EPS makes the membrane pore irreversible fouled.

Figure 6 shows typical SEM photos of the fouled membrane and that after 1-min backwash. The normal backwash could not effectively recover the membrane, as a substantial amount of sludge was still retained on the membrane surface as compared with unfouled membrane. The 1-min backwash per 48 h was found adequate to remove the bio-cake attached on the membrane surface. This frequency controls EPS accumulation on the membrane at 23.2 mg/g MLSS. When power failure occurred, the bio-cake attachment could not be washed away from membrane surface in time. The same situation was found in re-construction of the situation with aeration suspended for 30 h, in which biomass in the bio-cake layer became dead throughout the layer. A substantial amount of EPS (121.8 mg/g MLSS) was released. This explained the TMP jump when EPS concentration exceeded 100 mg/g MLSS (Meng et al. 2006; Zhang et al. 2006; Hwang et al. 2008).

CONCLUSIONS

The pilot plant of our low-cost MBR was successfully operated for 370 days without fouling except for the acciden-
tal power failure for 30 h. The plant produced steady and good quality effluent which adequately met the Hong Kong secondary sewage discharge standards. The average effluent TN, COD, and SS were 7.7, 27 and 15 mg/L, respectively. The maximum effective permeate flux was up to 4.8 m/d under an air-to-water volumetric ratio of 15. TMP was maintained at 0.1 bars after 1-min backwash in every 48 h using about 1% of permeate. Membrane fouling happened only when aeration stopped for more than 30 h, which is caused by EPS increase in the reactor as well as the bio-cake on the membrane surface.

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REFERENCES


