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Optimization of operating variables in a pilot-scale reverse osmosis membrane process for reclamation of tunnel construction wastewater

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ABSTRACT

The goal of this study was to investigate the individual and combined effects of temperature, salinity, and pressure on permeate flux and salt rejection of the reverse osmosis (RO) process used for reclamation of tunnel construction wastewater. Regardless of changes in temperature, higher operating pressures enhanced both permeate flux and salt rejection, while effects of temperatures on performance varied depending on the operating pressures. Increasing temperatures to less than 35 bar did not improve the permeate flux and salt rejection, while to more than 50 bar led to higher rejection as well as more permeate flux of reclaimed wastewater. Based on analysis of model equations developed, the extent of flux and salt rejection required for reuse of the reclaimed wastewater occurred under different optimal conditions depending on variations in seasons and salinity of wastewater. In particular, it was necessary to add additional pressure exceeding 50 bar or increase the temperature to over 20°C when wastewater of more than 20‰ salinity flows into the treatment system. Adjustment of influential variables can provide an implementable approach to improve operation of the RO process as well as optimize a process for practical construction on-site applications.

Keywords: Tunnel construction wastewater; Optimization; Reverse osmosis; Salt rejection; Permeate flux

1. Introduction

In recent decades, human activities have decreased the availability of potable water, leading to efforts to develop alternative usable water resources. The reuse and recycling of reclaimed wastewater is considered to be a strategic option of water resource management. It is particularly attractive in situations where the available water supply is already overcommitted and cannot meet ever expanding water demands of a growing community. Generally, conventional wastewater treatment systems such as coagulation–flocculation and sedimentation cannot successfully satisfy the suggested standards of reclaimed wastewater reuse [1]. As a competitive alternative or addition

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to traditional wastewater treatment technologies, membrane filtration has been employed to remove various wastewater contaminants by providing highly selective separation processes for water reuse [2,3]. In particular, reverse osmosis (RO) is by far the most prevalent membrane-based desalination process for sea water desalination and wastewater reclamation [4]. Using nanofiltration and RO membranes, the quality of water obtained via filtration of the petroleum industry's wastewater attains the standards for reuse as indirect potable water [5]. Also, a dual membrane process combining microfiltration (MF) and RO has been successfully applied to meet the water quality criteria for municipal wastewater reclamation and reuse [2,6].

Wastewater targeted in this study was generated during tunnel construction including tunneling excavation, draining, and grouting to seal in water. High concentrations of suspended solids (SS) containing significant amounts of fine cement and sand were the main pollutants in the wastewater, resulting in high turbidity [1,7]. Moreover, since the tunnel construction site targeted was located in a coastal area, salinity in the wastewater posed an additional challenge with its concentration variation depending on the specific sites of the excavation work. For these reasons, an RO-based wastewater reclamation system coupled with coagulation and MF was employed in this coastal site to potentially achieve on-site water reuse with the dual aims of helping to extend available water supplies while reducing environmental contamination [1]. However, the performances of RO membranes—permeate flux and salt injection—were highly affected by influential variables such as temperature and feed water salt concentration [8] since the on-site reclamation system was exposed to external environmental conditions. Different environmental conditions in wastewater systems create different optimal conditions for membrane processes [9]. Therefore, selectively optimizing the RO process was required depending on variations in temperature and salt concentrations. Also, it was necessary to analyze the interactions as well as the main effects of the influential variables affecting RO process performance. Although many studies have reported RO efficiency in sea water desalination [10,11], optimization of operating conditions for an on-site RO-based wastewater reclamation system has not yet been attempted. The primary objectives of this study are to: (1) illustrate the interaction between operating conditions (salinity, temperature, and pressure) and RO process performance; and (2) optimize the process for use in construction on-site applications using central composite design (CCD) of response surface methodology (RSM).

2. Materials and methods

2.1. Description of a system configuration

The tunnel construction site was located in a coastal area, Yeongdo, Busan, South Korea (Fig. S1a). The tunnel with a total length of 1,480 m and a depth of 60 m below ground level was used to lay electrical power or telecommunication cables. During this study, wastewater approximately at the rate of 1,000 m^3/d was generated on-site. Wastewater treatment consisted of three successive stages: (1) coagulation, (2) zeocarbon filtration, and (3) membrane filtration (Fig. S1b). A pilot-scale, combination three-stage system was operated on-site for 90 d for reclamation of tunnel construction wastewater. Variations in the wastewater characteristics passing through the pilot system are summarized in Table S1.

The alum-based coagulation process was designed having a height of 2.0 m and inside diameter of 0.45 m. Effluent from the coagulation process was passed through filtration media in a carbon filtration process adding an activated carbon charcoal and zeolite mixture. Effluent collected from the column outlet was subjected to the following membrane filtration process. The continuous membrane filtration process comprised of MF and RO membranes. The MF membrane was applied for removing aggregates and particles as a pretreatment option for RO. The spiral-wound type MF membrane (Woongin Chemial Co., Ltd, Korea) consisted of polypropylene having a pore size of 0.5 μm. Two MF modules were operated in dead-end mode and backwashing was performed with air stripping. The MF permeate was further filtered using spiral-wound polyamide type, thin-film composite RO membranes (Woongin Chemial Co., Ltd, Korea). The salt rejection of the element is 99.6% as determined using 32,000 mg/L NaCl solution at an applied pressure of 5.5 MPa (25˚C). The RO unit section consisted of one module, consisting of a one-step, one-stage system (effective membrane areas of 2.2 m^2; permeate flux of 1.9 m^3/d).

2.2. Experimental design

The RSM experiment using CCD was employed to investigate the mutual effect and relative significance of three input factors affecting the performance of the RO process (permeate flux and salt injection). Experiments designed by Design-Expert version 7 were conducted at three different levels of concentration (A), temperature (B), and pressure (C) of feed water. The coded values for A, B, and C are set at five levels: −1 (minimum), 0 (central), +1 (maximum), and two outer points corresponding to α value of 1.68

(Table 1). CCD consisting of 6 center points and 14 axial points that rendered a total of 20 experimental runs was used to analyze the data acquired from the experimental runs (Table 2). These data were then used to optimize the performance of the RO process. All coefficient variables were analyzed by multiple regression analysis and a response contour plot was generated using the software Design-Expert version 7. Validity of the selected model used for optimizing the process parameters was tested using analysis of variance (ANOVA).

For the RO filtration experiments, synthetic wastewater in the feed tank was pumped to the RO membrane module (Table S2). The membrane having an effective area of 2.2 m^2 with a spiral-wound configuration was studied. The required temperature of feed wastewater was controlled using a cooling/heating system. NaCl solutions for variations in feed concentration were used in a module feed stream. The needed pressure was controlled by the pressure valve. The volume of permeated water collected during a designated period (60 min) was determined using a cylinder. The salt concentration of the collected water was analyzed using an ion chromatograph. Periodic cleaning was conducted after finishing each filtration test. A NaOH aqueous solution of 1,000 mg/L was used as the alkaline cleaning agent to wash the membranes for the first 20 min of each cleaning step, followed by a 5 min rinsing with pure water to remove the particle-packed layer, which might be embedded on the membrane surface.

Table 1
Experimental range and level coded of independent variables

Variable	Symbol	Coded levels				
		$-\alpha$	−1	0	1	$+\alpha$
Salinity (‰)	A	3.18	10	20	30	36.82
Temperature (℃)	B	5.18	12	22	32	38.82
Pressure (bar)	C	23.18	30	40	50	56.82

2.3. Analytical methods

Water temperature and pH were measured using a portable meter (HM-21P, TOA-DKK Co., Hong Kong). Turbidity was determined using a laboratory turbidity meter (2100AN, HACH, USA). Concentrations of SS, chemical oxygen demand, NH_4^+−N, total nitrogen, total phosphorus, Al, Fe, and Mn were determined according to a standard method [12]. Chloride and salinity were measured with an ion chromatograph (ICS-1000, Dionex Co., USA) and a portable digital refractometer (PR-100SA, Atago, Japan), respectively.

Table 2
CCD matrix for three variables along with observed responses

Run	Variables			Responses	
	Salinity (A, ‰)	Temperature (B, ℃)	Pressure (C, bar)	Permeate flux (L/m^2 h)	Salt rejection (%)
1	10	12	30	5.77	99.85
2	10	12	50	10.40	99.93
3	30	12	30	2.67	99.82
4	30	12	50	6.85	99.82
5	20	22	40	8.25	99.82
6	20	22	40	8.55	99.80
7	20	22	40	8.62	99.83
8	20	22	40	8.70	99.84
9	20	22	40	8.64	99.83
10	20	22	40	8.58	99.82
11	20	22	23.18	3.50	99.79
12	20	22	56.82	13.40	99.86
13	10	32	30	9.56	99.81
14	10	32	50	17.92	99.87
15	30	32	30	3.59	99.77
16	30	32	50	9.35	99.93
17	3.18	22	40	12.79	99.88
18	36.82	22	40	3.08	99.94
19	20	5.18	40	5.57	99.84
20	20	38.82	40	11.31	99.84

3. Results and discussion

3.1. Statistical analysis

A total of 20 experiments using the CCD were conducted to determine the effect of the factors on two characteristic responses: permeate flux and salt rejection. Table 2 represents the experimental design matrix and the results of the response variables obtained from the experiments. In order to create a better model, variable selection techniques were used. A backward elimination procedure was employed to eradicate any insignificant terms and ANOVA results of this reduced cubic model. Removing the insignificant terms produced the following models for each response that are more effective as a predictor of new data (Eqs. (1) and (2)):

$$\begin{aligned}\text{Permeate flux } (\mathrm{L/m^2h}) = & -1.32 + 0.04A + 0.18B \\ & + 0.10C - 0.009AB \\ & + 0.002AC + 0.012BC \\ & - 0.002A^2 - 0.005B^2 \\ & - 0.0003ABC + 0.0002AB^2\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Salt rejection } (\%) = & \ 100.03 - 0.013A - 0.025B + 0.008C \\ & + 0.0007AB - 0.0004AC \\ & - 0.00024BC + 0.0003A^2 + 0.0007B^2 \\ & + 2.03E-05AB - 3.16E-05AC\end{aligned} \tag{2}$$

where salinity is (A); temperature, (B); and pressure, (C). A positive sign in front of a term designates a synergic effect, while a negative sign designates an antagonistic effect, indicating the influence of independent variables on the RO process.

ANOVA for the response surface cubic model for the performance of RO process—permeate flux and salt rejection—was used to justify the adequacy of the model as shown in Tables 3 and 4. The least square regression was used to fit the obtained results. ANOVA for permeate flux of the RO process represented in Table 3 indicates that the F-value of 1,115.655 implied that the cubic model was significant because model terms which have a "Prob > F" values of less than 0.05 are considered to be significant, while values greater than 0.1 are insignificant [13]. From Table 3, it is evident that the linear terms for salinity (A), temperature (B), and pressure (C) had extremely large effects on the permeate flux of the RO process, indicating very high F-values. In particular, pressure (C) among these linear terms represented the most significant parameter effect on the permeate flux. In the case of ANOVA for the salt rejection, F- and p-values were 13.369 and 0.0003, respectively (Table 4). Unlike the ANOVA for permeate flux representing significance of linear terms for all variables, the ANOVA for the salt rejection indicated that only the linear term for pressure (C) was significant (F-value = 42.83), while the linear terms for salinity (A) and temperature

Table 3
ANOVA for permeate flux of the RO process

Source	Sum of squares	df	Mean square	F-value	p-value Prob > F
Model	275.255	10	27.525	1,115.655	<0.0001
A-Salinity	47.131	1	47.131	1,910.318	<0.0001
B-Temperature	43.586	1	43.586	1,766.623	<0.0001
C-Pressure	114.662	1	114.662	4,647.434	<0.0001
AB	7.778	1	7.778	315.266	<0.0001
AC	1.162	1	1.162	47.080	<0.0001
BC	3.522	1	3.522	142.757	<0.0001
A^2	0.674	1	0.674	27.303	0.0005
B^2	0.019	1	0.019	0.762	0.4053
ABC	0.589	1	0.589	23.879	0.0009
AB^2	0.187	1	0.187	7.560	0.0225
Residual	0.222	9	0.025		
Lack of fit	0.098	4	0.025	0.995	0.4876
Pure error	0.124	5	0.025		
Cor total	275.477	19			
Std. Dev.	0.157		R^2	0.999	
Mean	8.354		Adj R^2	0.998	
C.V. %	1.880		Pred R^2	0.994	
PRESS	1.753		Adeq Precision	130.564	

Table 4
ANOVA for salt rejection of the RO process

Source	Sum of squares	df	Mean square	F-value	p-value Prob > F
Model	0.039	10	0.00385	13.369	0.0003
A-Salinity	0.002	1	0.00172	5.953	0.0374
B-Temperature	0.000	1	0.00025	0.869	0.3757
C-Pressure	0.012	1	0.01235	42.833	0.0001
AB	0.004	1	0.00385	13.358	0.0053
AC	0.000	1	0.00009	0.296	0.5996
BC	0.002	1	0.00219	7.594	0.0223
A^2	0.013	1	0.01314	45.593	<0.0001
B^2	0.000	1	0.00028	0.961	0.3525
ABC	0.003	1	0.00331	11.465	0.0081
AB^2	0.003	1	0.00331	11.488	0.0080
Residual	0.003	9	0.00029		
Lack of fit	0.002	4	0.00043	2.498	0.1713
Pure error	0.001	5	0.00017		
Cor total	0.041	19			
Std. Dev.	0.017		R^2	0.937	
Mean	99.844		Adj R^2	0.867	
C.V. %	0.017		Pred R^2	0.076	
PRESS	0.038		Adeq Precision	13.093	

(B) were insignificant corresponding to 5.95 and 0.86 F-values. However, the quadratic term for salinity (A) had a large F-value of 45.59 and a p-value < 0.0001. Thus, the effect of the salinity of feed water on the salt rejection is strongly modeled with the quadratic term. For the statistics used to test the adequacy of the models, the coefficients of determination (R^2) were 0.99 and 0.94, respectively, indicating that 99 and 94% of the variability in the data was accounted for by the models. It is suggested that for a good fit, model R^2 should be approximately 1 and should be at least 0.80 [14]. All the statistics given in Tables 3 and 4 indicate that the estimated models for each response fit the experimental data adequately, implying that the models were reliable for both permeate flux and salt rejection of the RO process in this study.

3.2. Effects of variables on performance of the RO process

Effects of the variables' interactions on the performance of the RO process—permeate flux and salt rejection—were investigated by plotting three-dimensional (3D) response surfaces (Fig. 1). Fig. 1(a) and (b) exhibits the 3D surface plots of permeate flux and salt rejection vs. two variables (temperature and pressure) at a fixed value of the third variable (at 20‰ salinity of feed water). An increase in both temperature and pressure caused a rise in the amount of permeate flux, but the effect of the feed water pressure was more than that of the temperature on the permeate flux (Fig. 1(a)). Higher feed water pressures, regardless of seasonal change (variations in temperature of feed water), increased water flux across the RO membrane. Meanwhile, higher temperatures (in summer) at a fixed pressure allowed more permeate flux of reclaimed wastewater from the RO process due to the higher diffusion rate of water through the membrane, but the increasing ambient temperature at lower pressures (less than 35 bar) did not improve the permeate flux (Fig. 1(a)). From the surface plot demonstrating the effects of the variables on salt rejection shown in Fig. 1(b), increased feed water pressure at different fixed temperatures also led to increased salt rejection. Although salt rejection above a certain pressure level could not be increased any further [15], the experimental range of pressure in this study did not allow identification of the upper limits of salt that can be excluded via increasing the feed water pressure. Meanwhile, the effects of the temperature of feed water on salt rejection varied depending on the degree of pressure (Fig. 1(b)). Higher temperatures of feed water at more than 50 bar of pressure led to higher salt rejection from wastewater, while at less than 40 bar resulted in lower salt rejection due to a higher diffusion rate for salt through the membrane. This indicates that the feed water pressure in the RO process reclaiming tunnel wastewater should be properly controlled to accommodate seasonal fluctuations in temperature to satisfy regulatory standards of salt concentrations for the reclaimed wastewater reuse.

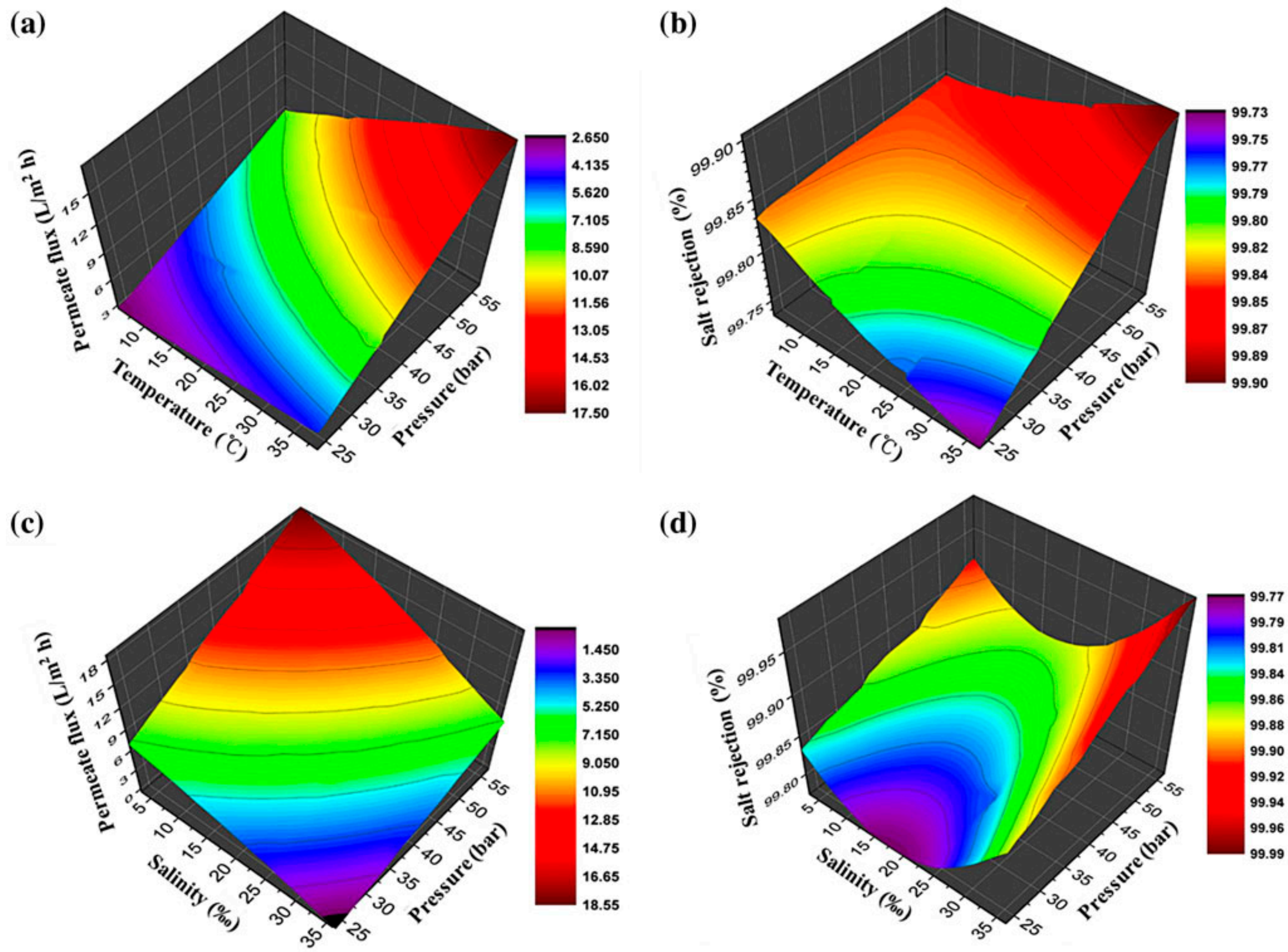

Fig. 1. Three-dimensional contour plots of (a) permeate flux; (b) salt rejection showing effects of temperature and pressure at 20‰ salinity; (c) permeate flux; (d) salt rejection showing effects of salinity and pressure at 22℃.

Fig. 1(c) and (d) shows the interactions of salinity and pressure on permeate flux and salt rejection at a fixed temperature of 22℃ of feed water, respectively. Pressure had a positive effect on the permeate flux, whereas salinity had a negative effect (Fig. 1(c)). The negative effect of salinity as shown in Fig. 1(c) demonstrates that higher salt concentrations led to lower RO membrane water flux given a constant applied pressure, reflecting that the increase in osmotic pressure offsets the feed water driving pressure [16]. When salt concentrations in wastewater increase, the operating pressure should be increased to maintain the flux of reclaimed wastewater for reuse. As can be seen in Fig. 1(d), salt rejection was enhanced with higher operating pressures due to dilution by higher water flux [17]. Generally, increase in salt concentration leads to increase in salt flux due to a higher concentration gradient inside the membrane [18]. In this study, the salt rejection of the RO process decreased from 99.92 to 99.74% as the salinity of the wastewater increased from 3.18 to 20‰, consistent with previous reports (Fig. 1(d)) [18,19]. When salinity exceeds 20‰, however, the salinity positively affected salt rejection despite an increase in salt passage by a decline in water flux. This might be due to increase in the difference between the feed and permeate concentrations resulting from small variations in permeate concentrations despite an increase in feed concentrations, resulting in an increase in the salt rejection.

3.3. Optimization of performance of the RO process

Optimization of operating parameters was carried out based on 2D contour plots of the model describing both permeate flux and salt rejection of the RO process depending on variations in temperature, pressure, and salinity (Fig. 2). Holding the salinity of the wastewater fixed at 10‰, concentrations of chloride

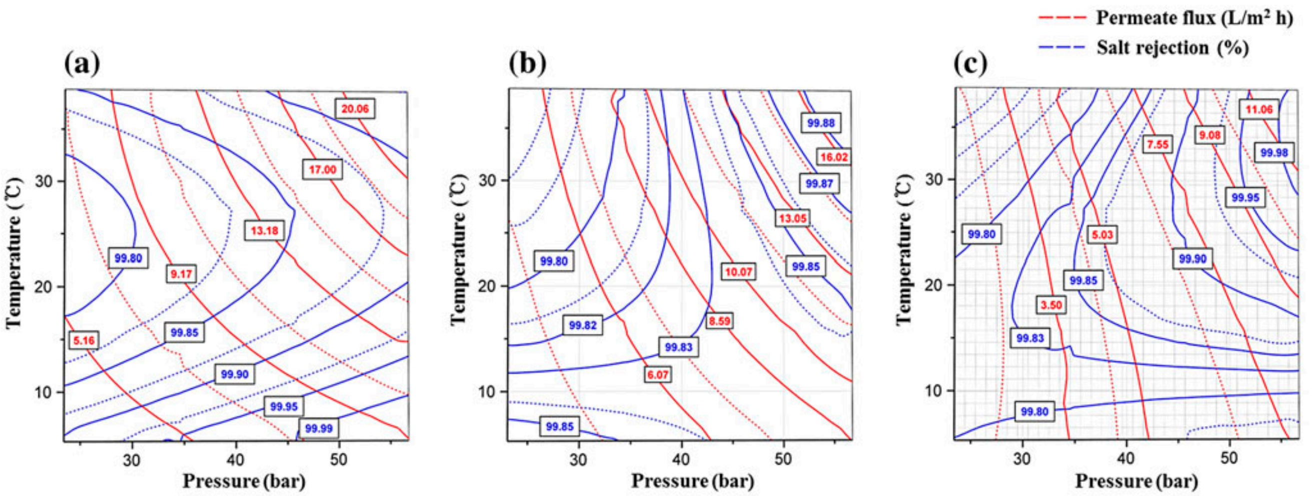

Fig. 2. Two-dimensional contour plots of the model describing both permeate flux and salt rejection of the RO process depending on variations in temperature and pressure at (a) 10‰; (b) 20‰; and (c) 30‰ salinity.

ion in the permeate during all seasonal changes (6–27℃) were produced to satisfy reuse application of the treated wastewater (less than 30 mg/L corresponding to 98.80% of salt rejection) (Fig. 2(a)). However, at temperatures of approximately 6℃, operating pressure had to be increased to more than 50 bar to attain production of reclaimed wastewater (0.5 m^3/d corresponding to around 9.8 L/m^2 h). Also, with operating pressures of less than 40 bar in winter, the temperature of feed water should be controlled by heating to over approximately 15℃. As temperature increased from 16℃ (spring or fall) to 27℃ (summer), the required operating pressure gradually decreased from 37 to 32 bar, reflecting an increase in water flux by a higher diffusion rate of water through the membrane at higher temperatures (Fig. 2(a)).

Regarding the inflow of wastewater of higher salinity into the process (at 20 and 30‰ salinity) (Fig. 2(b) and (c)), application of higher pressures (more than 50 bar) or increasing the temperature (over 20℃) should be chosen to achieve both the proposed chloride ion concentrations (less than 30 mg/L) and production (0.5 m^3/d) of reclaimed wastewater in all seasons. Even during winter, the RO process varying only the operating pressure did not produce any permeates meeting both requirements. Alternately, in order to minimize the operating costs of increasing temperature or pressure, the required extent of salt injection (quality) or production rate (quantity) should be changed regardless of seasonal variations in the high salinity wastewater. Attaining the required production rate led to a compromise in the quality of the permeate not satisfying the regulations for reuse of the reclaimed wastewater which required more discharge of the treated effluent outside (concentration of chloride ion in the effluent satisfied the standards of discharge of wastewater). Or, to satisfy the quality of the permeate, the required production rate should be decreased. Consequently, the desired performance of the RO process treating tunnel construction wastewater occurred under various conditions depending on variations in seasons and salinity of wastewater. Also, analyzing these results could allow development of model equations allowing prediction of the combined effects of temperature, salinity, and pressure on both permeate flux and salt rejection in the RO process reclaiming wastewater of high salinity. For example, a calculation using the equation developed here would provide helpful information to optimize both design and operation of a process for practical construction on-site applications.

4. Conclusions

Wastewater treatment performance using an RO process depended on the combined effects of temperature, salinity, and pressure. Increasing the operating pressure increased both permeate flux and salt rejection regardless of seasonal changes, while the effects of temperature on those were driven by the operating pressure. Higher feed concentrations decreased the permeate flux, while salt rejection was reduced only in the range of less than 20‰ salinity. To optimize operations, the RO process should be controlled to accommodate variations in seasonal temperatures and feed concentrations.

Supplementary material

The supplemental material for this paper is available at http://dx.doi.org/10.1080/19443994.2015.1049406.

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