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Effect of chemical pretreatment on the silt density index of brackish water from north and south Kuwait

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ABSTRACT

In this study, the effect of chemical pretreatment with powdered activated carbon (PAC), ferric chloride, and aluminum chloride at the different concentrations of 10, 30, and 60 ppm on the silt density index (SDI) value of brackish water was examined. Generally, PAC pretreatment was found to be the best pretreatment method. Pretreatment with 10 ppm of PAC resulted in the lowest SDI value of 3.5, which is approximately 44.4% lower than untreated brackish water. After pretreatment with PAC, scanning electron microscopy (SEM) of the filter surface showed large graphite-like particles. An intermediate blocking mechanism produced the best fit for the filtration data from PAC pretreatment. The SEM images of the filter surface show a thick cake layer formation in the aluminum chloride and ferric chloride pretreatments. The cake filtration blocking mechanism was the best fit for brackish water treated with aluminum chloride and ferric chloride.

Keywords: Brackish water; Silt density index; Pretreatment; Ferric chloride; Aluminum chloride; Powdered activated carbon

1. Introduction

Due to the increase in water demand, Kuwait may face a water shortage problem in the near future, which may possibly become a crisis if no measures are taken to address this situation [1]. One of the few limited water sources in Kuwait is the brackish water in south and north Kuwait in the Wafra and Abdily areas, respectively. The quality of Kuwait groundwater varies from brackish to highly saline in the southwest to the northeast corners of Kuwait, respectively [2]. In addition to the increasing water demands of Kuwait, there has been growth in the agricultural activities in the Wafra and Abdily areas. The brackish water is treated by reverse osmosis (RO) filtration systems to produce low-salinity water suitable for crop irrigation. Most of the RO systems used on Kuwaiti farms do not have a feed pretreatment system, resulting in a severe fouling problem and low productivity.

RO is a widely implemented technology used to desalinate and purify surface water, brackish water, sea water, and wastewater to produce drinking water. The success of RO desalination technology is due to lower energy requirements and the ease of

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construction, operation, and scaling up compared with old desalination technology, such as multi-flash distillation technology [3–5].

An estimated 43% of the world's water production uses the RO desalination method [6–8]. Fouling is a major problem in RO desalination, which reduces the economically successful implementation of the technology [9]. The fouling sources in brackish water desalination using RO systems are scale fouling by metal ions, biofouling by bacteria, organic fouling by humic acid and oils, and silt fouling by particulate matter. However, previous studies show that silt fouling by particulate matter is the major fouling category [9].

Numerous researchers have studied the effects of various pretreatment chemicals and chemical dosages on the fouling of RO membranes used to filter surface water and sea water [9–14]; however, studies on brackish water are limited. Moreover, studies on the effect of chemical pretreatment on the membranes of desalination systems are not in total agreement and sometimes contradict each other.

In their study, Kimura et al. found that using a higher dosage of polyaluminum chloride (PACl) for surface water coagulation resulted in severe irreversible fouling in a 0.1 μm microfilter membrane [11]. Shrive et al. reported a sharp decline in the microfiltration membrane flux used to treat Ohio River water after using 1–5 mg/L of alum or PACl coagulants [12]. On the other hand, the pretreatment of natural surface water with ferric salts resulted in increasing the membrane flux by 25–50% compared with untreated water flux in a pilot study by Braghetta et al. [13]. Laine et al. reported an improvement in the membrane terminal flux from 20 to 60 percent using 60 mg/L of PACl for a hydrophilic membrane and a 10% increase for a hydrophobic membrane for surface water filtration [14].

Coagulation and flocculation of the fouling materials in the feed water caused by chemical pretreatment can block the membrane pores in several ways. Hermia [15] has proposed four different fouling mechanisms for dead end constant pressure filtration in which particles foul the membrane, which are shown in Eq. (1):

$$\frac{d^2t}{dV^2} = K\left(\frac{dt}{dV}\right)^n \quad (1)$$

where t is the filtration time, V is the filtrate volume, k is the resistance coefficient, and n is the blocking index. Complete blocking ($n = 2$) occurs when a single particle completely blocks each membrane pore without another particle being superimposed, intermediate blocking ($n = 1$) occurs when particles larger than the membrane pore block the membrane, standard blocking ($n = 1.5$) occurs when particles smaller than the membrane pore are adsorbed onto the internal walls of the pore and narrow the flow channel, and cake filtration ($n = 0$) occurs when a cake layer is formed on the membrane surface. Fig. 1(a)–(d) are adaptations of the four blocking mechanisms [15,16].

To operate and maintain a successful desalination system, an effective pretreatment system should be installed to eliminate particulate and organic fouling of membrane systems. An established measure of the effectiveness of pretreatment systems is the measurement of the silt density index (SDI) of the treated feed water.

The SDI is one of the most important feed parameter measurements in the design and operation of reverse osmotic desalination systems. The measured value of the SDI is widely accepted as an indicator of the fouling potential for treated feed water. Most reverse osmotic membrane manufacturers require feed water with an SDI of less than three [17]. Furthermore, at low turbidity, the SDI has been found to be the most accurate method to predict the performance of RO desalination systems [18]. In this research, the effects of different pretreatment chemicals on the SDI and the blocking mechanisms of the treated Kuwait brackish water were examined in a systematic way. The effect of the different blocking mechanisms on the SDI microfilter for each pretreatment method was examined.

2. Materials and methods

In the first stage of this study, the SDI of brackish water was measured at 5, 10, and 15 min (Eq. (2)) for 20 farms in the Wafra and Abdily areas (10 from each area) in south and north Kuwait, respectively. The total dissolved solids (TDS), electrical conductivity (EC), and pH were measured for all brackish water samples:

$$\mathrm{SDI} = \frac{1 - (t_i/t_f)}{t_t} \times 100 \quad (2)$$

where t_i is the initial filtration time to filter a fixed volume (500 mL) in seconds, t_f is the final filtration time to filter a fixed volume (500 mL) in seconds, and t_t the total elapsed time of the experiment in minutes (5, 10, or 15).

An automatic SDI System (Y-SIMPLESDI-220, Applied Membranes, Inc., USA) was used to measure

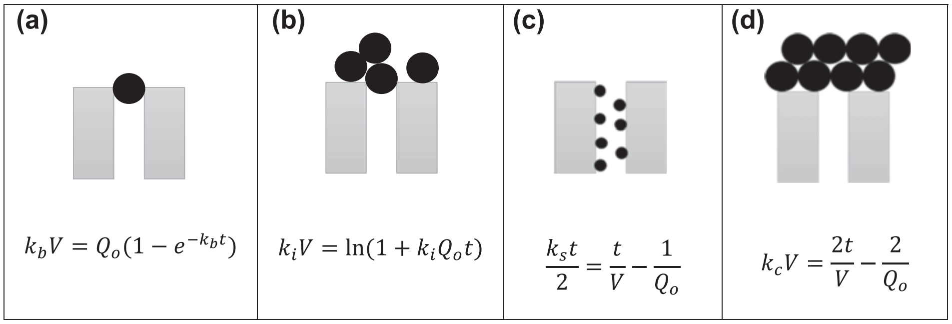

Fig. 1. Filtration blocking mechanisms: (a) complete blocking, (b) intermediate blocking, (c) standard blocking, and (d) cake filtration. (Q_o is the initial flow rate, K_b, s, i, c is the constant for each blocking mechanism, V is the total filtered volume, and t is the filtration time).

the SDI of the brackish water samples (Fig. 2). Millipore cellulose acetate with 0.45 μm microfilters were used for all filtration experiments. The pH value for each sample was measured using a Basic Portable pH Meter (HI 8010, HANNA Instruments, USA). The EC and TDS were measured using an EC/TDS/℃/NaCl Meter (HI 9835, HANNA Instruments, USA).

In the second part of this study, brackish water with the highest SDI value from the Wafra area was selected for the pretreatment experiments. The brackish water samples were treated with powdered activated carbon (PAC), aluminum chloride, and ferric chloride. All chemicals used in this study were of ACS grade. The appropriate amount of each chemical was measured using a sensitive balance. In each pretreatment experiment, a 30 L solution was prepared with concentrations of 10, 30, and 60 ppm. The brackish water was mixed with the pretreatment chemicals for 10 min at high speed (500 RPM) and then for 20 min at a lower speed (150 RPM) using a Servodyne mixer (Cole-Parmer Instrument, Veron Hills, USA) with a high-lift blade. The treated water was allowed to settle overnight, and the clear supernatant water from the top was used for the SDI experiments. Each experiment was repeated three times for each concentration, and the average values of the SDI were calculated. The temperature was maintained at 24℃ during the entire experiment.

The blocking models shown in Table 1 were used to estimate the blocking mechanisms using the filtration data. The mean squared errors of the complete, standard, intermediate, and cake filtration blocking

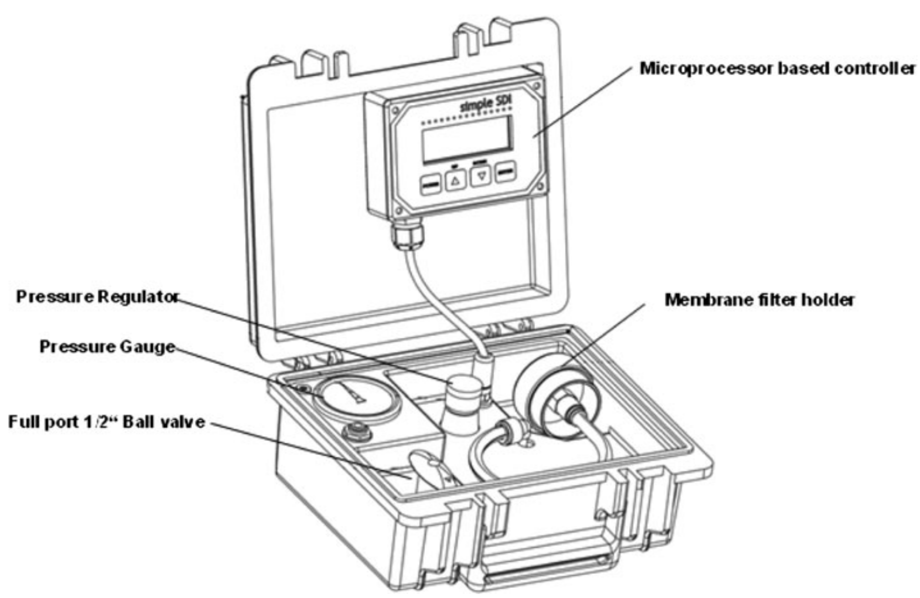

Fig. 2. Automatic SDI system.

Table 1
Analysis results of brackish water from the Wafra and Abdily areas

	Measured variable	Maximum	Minimum	Average
Wafra	pH	7.50 ± 0.04	6.89 ± 0.07	7.19 ± 0.17
	TDS (g/L)	8.28 ± 0.03	3.09 ± 0.09	6.06 ± 1.61
	EC (mS/cm)	15.35 ± 0.21	6.08 ± 0.03	11.86 ± 2.94
	SDI-15	5.8 ± 0.1	3.3 ± 0.4	4.6 ± 0.99
Abdily	pH	7.90 ± 0.01	7.11 ± 0.10	7.54 ± 0.24
	TDS (g/L)	8.50 ± 0.00	3.80 ± 0.01	5.83 ± 1.39
	EC (mS/cm)	17.00 ± 0.01	7.60 ± 0.01	11.64 ± 2.71
	SDI-15	5.9 ± 0.17	1.5 ± 0.60	3.9 ± 1.4

models were calculated using the experimental filtration data to determine the best fitting mechanism.

High-resolution images and elemental data analyses for the microfilters used in the SDI filtration experiments were obtained by scanning electron microscopy (SEM) (JSM-6010LV InTouchScope, JEOL, Japan). Energy dispersive X-ray spectroscopy (EDAX) was used to examine the topography and composition of the fouling layer.

3. Results and discussion

3.1. Part I: untreated brackish water analysis

The value of the pH, TDS, EC, and SDI for untreated brackish water samples from the Wafra and Abdily areas were measured in the first part of this study. The results are shown in Table 1.

3.1.1. Silt density index

The SDI values of most of the samples obtained in the Wafra area were typical for brackish water, ranging from 3.3 to 5.8 (Table 1). The SDI values of the samples from the Abdily area were lower, with minimum and maximum values of 1.5 and 5.9, respectively (Table 1). On average, the SDI values of Abdily's brackish water samples were lower than those of Wafra's brackish water samples, with average values of 3.9 and 4.6, respectively.

Twenty percent of the samples from Abdily had a SDI value of less than three, indicating that the brackish water can be fed to the RO desalination systems without the requirement of chemical pretreatment. However, none of Wafra's samples had an SDI value of less than 3. Moreover, 40 percent of the samples tested in the Abdily area and 60 percent in the Wafra area had SDI values between 3 and 5, indicating the requirement of frequent cleaning to ensure smooth operation of the RO systems. In addition, 40 percent of the tested samples of Abdily's and Wafra's brackish water had SDI values greater than 5, indicating a requirement for a pretreatment system before using the water as a feed for the RO desalination system.

3.1.2. TDS and EC

The values of the TDS, of the brackish water samples from the Wafra area, had a minimum value of 3.09 and a maximum value of 8.28 g/L. The EC values for all of the samples from the Wafra area had a minimum of 6.08 and a maximum of 15.35 mS/cm (Table 1). The TDS values for Abdily's brackish water samples had a minimum of 3.80 and a maximum of 8.50 g/L. The EC values for Abdily's samples had a minimum of 7.60 and maximum of 17.00 mS/cm (Table 1).

On average, the TDS values of Abdily's brackish water samples were lower than those of Wafra's samples. The average TDS value for Abdily's samples was 5.85, and for Wafra's brackish water samples, the value was 6.06 g/L.

3.1.3. pH value

The pH values of the brackish water samples were within a narrow range, ranging from 6.89 to 7.5 for Wafra's brackish water samples and from 7.11 to 7.90 for Abdily's brackish water samples (Table 1).

3.2. Part II: pretreatment experiments

3.2.1. Untreated brackish water

The untreated brackish water had average values of 14.8 ± 1.3, 8.7 ± 0.2, and 6.3 ± 0.2 for SDI-5, 10, and

15, respectively. The intermediate blocking mechanism (Fig. 1(b)) resulted in the lowest mean squared error for the filtration data of the untreated brackish water (Fig. 2), which indicated an accumulation of particles larger than the membrane pores on top of the microfilter pores. The SEM images of the filter surface show a high concentration of organic matter. Furthermore, EDAX analysis (Fig. 3) indicated a high concentration of silica, which is a possible indication of the presence of colloidal and/or single-cell (silica shell) diatom algae [19].

3.2.2. PAC pretreatment experiments

The SDI-15 average values for pretreatment with 10, 30, and 60 ppm of PAC were 3.5 ± 0.1, 4.1 ± 0.1, and 3.9 ± 0.1, respectively (Fig. 4). Increasing the concentration of PAC resulted in a higher SDI-15 value. The best result was obtained with a PAC concentration of 10 ppm (Fig. 4).

The SDI results at different concentrations of PAC are displayed in Fig. 3. The results show that the addition of 10 ppm PAC reduced the SDI to 3.5 compared with the SDI value of the untreated brackish water of 6.3. In addition, treatment with a higher dosage of PAC, 30 and 60 ppm, did not improve the SDI but increased the SDI value. It appears that the excess PAC did not precipitate and remained suspended in the solution, which traveled to the microfilter and increased its fouling. The lowest mean squared error (Fig. 5) was obtained with the intermediate blocking mechanism model (Fig. 1(b)), which indicated that the fouling material was larger than the pore size of the microfilter, and the external fouling was the dominating fouling mechanism. The SEM images show a dark black graphite-like layer covering the microfilter pores. Furthermore, EDAX does not show any traces of silica compared with the untreated brackish water, which suggests that PAC adsorbs colloidal silica and organic fouling materials.

3.2.3. Aluminum chloride pretreatment experiments

The average values of the SDI-15 for the aluminum chloride pretreatment experiment decreased with the increasing concentration of aluminum chloride. The average SDI-15 values for pretreatments with 10, 30, and 60 ppm of aluminum chloride were 5.0 ± 0.2, 4.9 ± 0.1, and 4.6 ± 0.6, respectively (Fig. 6).

The SDI values of brackish water treated with different concentrations of aluminum chloride were lower than the SDI value of untreated brackish water.

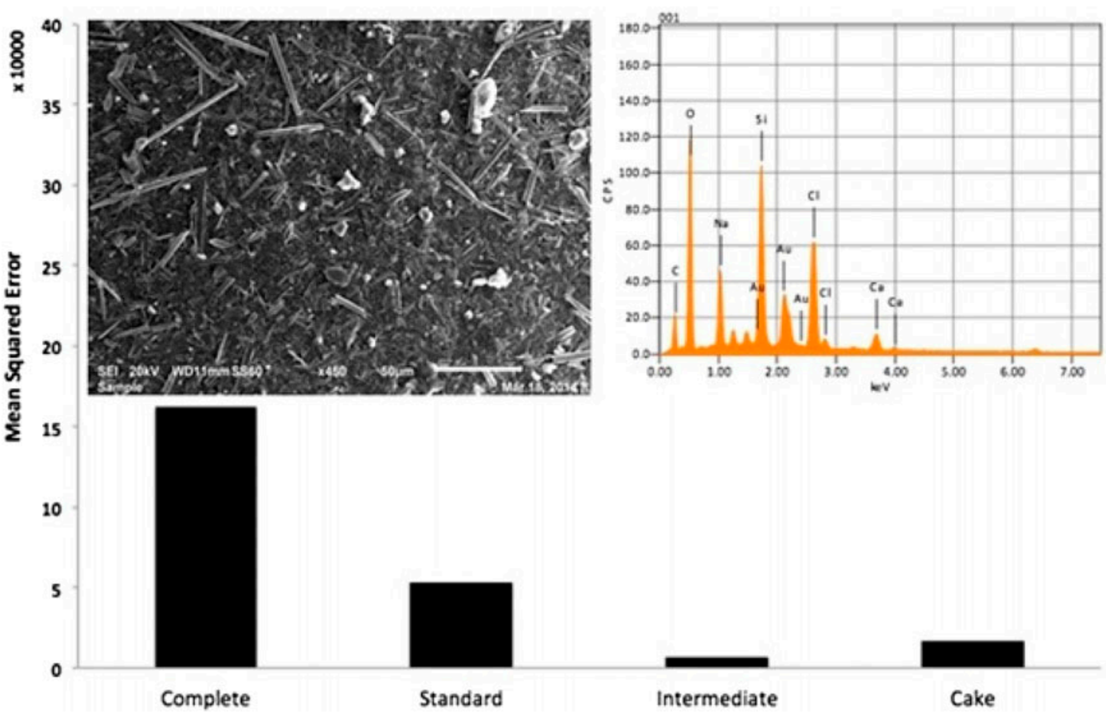

Fig. 3. Fitting of the blocking models, SEM and EDAX for untreated brackish water (Au peaks are due to the Au coating for the SEM–EDAX analysis).

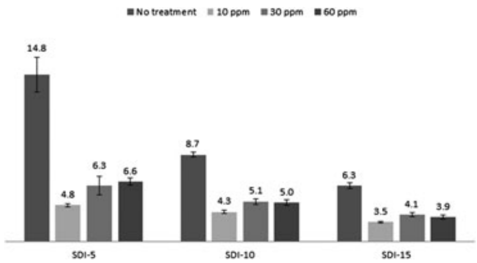

Fig. 4. Effect of pretreatment with PAC on the SDI of brackish water.

In addition, increasing the concentration of aluminum chloride resulted in an improved SDI value. The cake filtration models provided the best fit for the filtration data of the aluminum chloride-treated brackish water (Fig. 1(d)). The SEM images of the surface of the microfilter showed a thick cake layer (Fig. 7). In the case of treatment with aluminum chloride, it appeared that increasing its concentration resulted in increased sedimentation of the suspended particles in the brackish water, which was in contrast to the treatment with PAC, in which a higher concentration led to higher SDI values. Moreover, the silica concentration can be observed in the EDAX analysis at the same level as in the untreated brackish water. In addition, aluminum can be observed in the EDAX analysis of the cake layer on the top of microfilter surface (Fig. 7), suggesting that aluminum chloride does not adsorb silica and that the aluminum chloride is transported to the microfilter.

3.2.4. Ferric chloride pretreatment experiments

Increasing the concentration of ferric chloride did not improve the SDI values for the treated brackish water. The average SDI values after pretreatment with 10, 30, and 60 ppm of ferric chloride were 4.3 ± 0.3, 4.6 ± 0.1, and 5.1 ± 0.2, respectively (Fig. 8).

The values of SDI for brackish water treated with ferric chloride were lower compared with untreated brackish water. A similar effect was observed upon treatment with PAC. Increasing the concentration of ferric chloride increased the value of the SDI. The lowest SDI was obtained at the lowest ferric chloride dosage of 10 mg/L. The lowest mean squared error was achieved with the cake filtration model (Fig. 1(d)), which indicated the formation of cake layer on top of the microfilter (Fig. 9). The SEM images of the filter surface showed a uniformly dense cake layer covering the filter surface. It appears that coagulated particles did not completely settle and were transported with

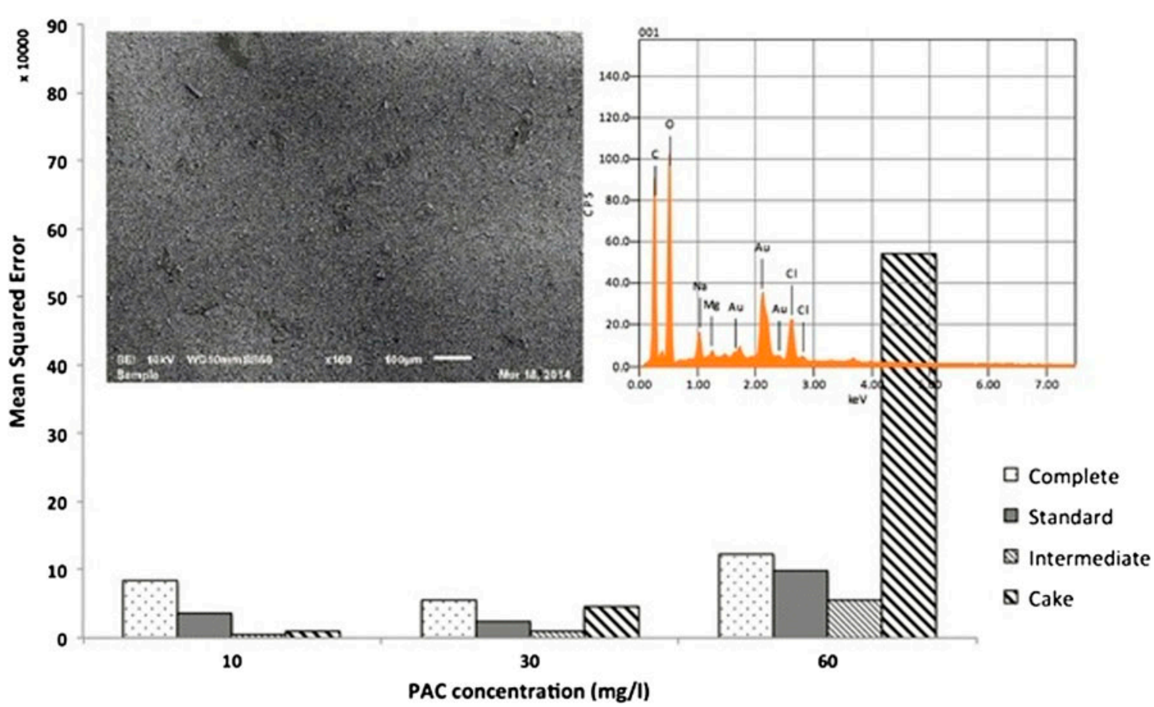

Fig. 5. Fitting of the blocking models; SEM and EDX for brackish water pretreated with PAC (Au peaks are due to the Au coating for the SEM–EDAX analysis).

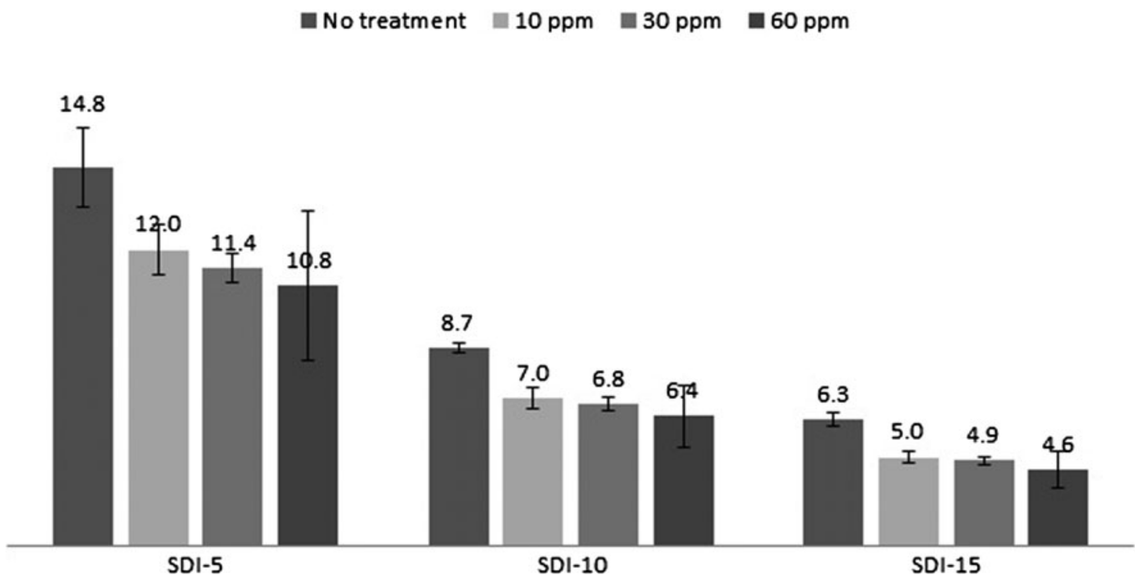

Fig. 6. Effect of pretreatment with aluminum chloride on the SDI of brackish water.

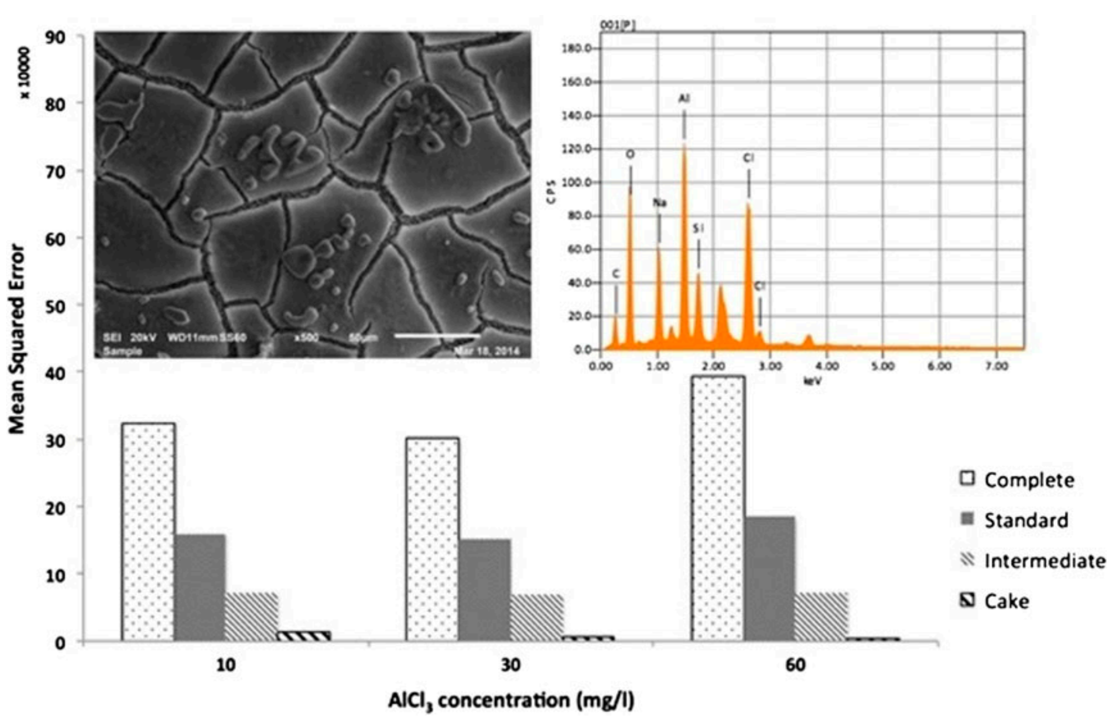

Fig. 7. Fitting of the blocking models; SEM and EDX for brackish water pretreated with $AlCl_3$.

the flow to the surface of the microfilter. EDAX showed a silica level similar to the level of the untreated brackish water. Ferric chloride can be observed in the EDAX analysis of the cake layer on the microfilter, indicating that the ferric chloride used in the pretreatment is reaching the microfilter (Fig. 9).

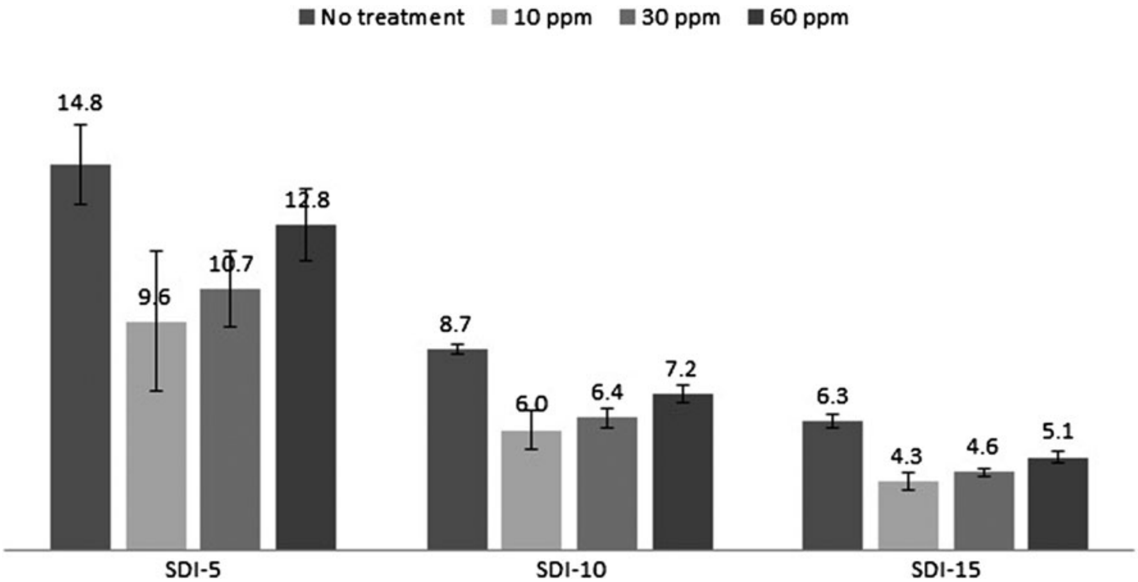

Fig. 8. Effect of pretreatment with ferric chloride on the SDI of brackish water.

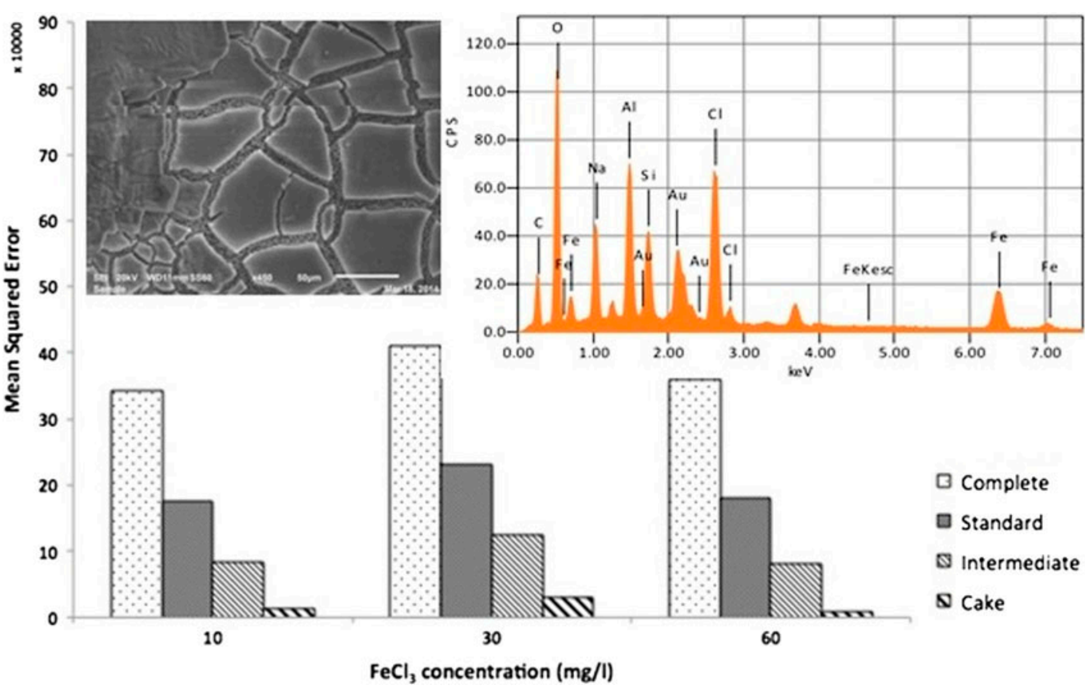

Fig. 9. Blocking models fitting; SEM and EDX for brackish water pretreated with $FeCl_3$ (Au peaks are due to the Au coating for the SEM–EDAX analysis).

4. Conclusion

The results of this study show high SDI values for both Abdily and Wafra untreated brackish water samples. Forty and 60 percent of the Abdily and Wafra brackish water samples, respectively, had SDI values greater than 3 and less than 5. An SDI value ranging from 3 to 5 indicates an increased likelihood of particulate fouling, and thus, frequent cleaning is required. A chemical pretreatment system is therefore required to use the brackish water as a feed for a reverse osmotic membrane desalination system.

Pretreatment with PAC produced the lowest SDI values. A lower concentration of pretreatment chemical resulted in a lower SDI value than a higher concentration for both PAC and ferric chloride. The opposite was true for aluminum chloride, for which a higher concentration resulted in lower SDI values. Increasing the concentration of pretreatment chemicals in the cases of PAC and ferric chloride had an adverse effect. The excess pretreatment chemicals plug the microfilter pores, thus increasing fouling and resulting in higher SDI values.

The pretreatment chemical dosing should be optimized depending on the type and concentration of fouling materials found in brackish water.

The intermediate blocking model was represented clearly, with the PAC pretreatment indicating that particles larger than the membrane pores block the membrane pores. On the other hand, aluminum and ferric chloride pretreatment showed the best fit with the cake filtration model, suggesting the formation of a cake layer over the membrane surface. The SEM images are in complete agreement with the blocking model's prediction of the fouling mechanisms. The EDAX analysis of the microfilter showed that silica (colloidal and organic) was the major fouling material in brackish water in Kuwait. This study showed that PAC was the best choice for treating brackish water in Kuwait.

Future studies should investigate the possibility of using a combined pretreatment rather than treating the brackish water with a single pretreatment chemical.

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