Ranking of antiscalant performance for gypsum scale suppression in the presence of residual aluminum

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Abstract

An approach to ranking antiscalant effectiveness for gypsum scale suppression using combined bulk crystallization and membrane scaling diagnostic tests was explored with a focus on the adverse impact of residual aluminum in dissolved ($\text{Al}^{3+}$) and as colloidal species on gypsum scale suppression. Five commercial antiscalants were ranked based on the crystallization induction time as determined in a well-mixed crystallization vessel with a back-light scattering turbidity meter to monitor gypsum formation. The presence of aluminum, even at trace levels (up to 100 $\mu$g/L), significantly reduced the crystallization induction time, thereby reducing antiscalant effectiveness. For a given antiscalant dose, the crystallization induction time decreased with increasing total aluminum concentration according to a log-linear relationship. Although the above qualitative behavior was similar for the tested commercial anti-scalants, the adverse impact of aluminum on antiscalants effectiveness differed markedly among the different antiscalants. Diagnostic scaling tests in a plate-and-frame RO module demonstrated antiscalant performance ranking of the same order as that obtained based on bulk crystallization induction time measurements.

Keywords: Aluminum; Gypsum; Mineral salt scaling; Antiscalant; Reverse osmosis; Pretreatment

1. Introduction

Successful application of membrane desalting requires feed pretreatment in order to reduce the potential for membrane fouling by colloidal, biological and organic matter, as well as by mineral scale. Antiscalants are commonly applied to suppress the formation of mineral scalants such as calcium sulfate (gypsum), calcium carbonate (calcite), barium sulfate (barite), and silica.
Various antiscalant formulations are commercially available for inhibition of mineral salt scale formation [1–11] and for silica fouling suppression [12,13]. Recent studies on RO desalting of Colorado River water have shown that, when conventional feed pretreatment is utilized using alum \([\text{Al}_2(\text{SO}_4)_3\cdot14\text{H}_2\text{O})]\), aluminum in the RO feed may be partially responsible for reducing antiscalant effectiveness and thus loss of scale inhibition control [14–16].

The technical product literature typically recommends that antiscalant inhibition of calcium sulfate, barium sulfate and calcium carbonate scale is most effective when the concentration of \(\text{Al}^{3+}\) is below about 50 µg/L. However, a rapid and quantitative diagnostic information is lacking in the published literature regarding the impact of aluminum on antiscalant effectiveness. Based on solution pH, various aluminum polymers and monomers are possible in RO influent waters. At circumneutral pH in the range of 7.5–8.5, aluminum is primarily found in the form \(\text{Al(OH)}_4^-\). Other forms of hydrated aluminum include \(\text{AlOH}^{2+}, \text{Al(OH)}_2^{+}, \text{Al}_3(\text{OH})_4^{5+}\), and \(\text{Al}_{13}\text{O}_{4}(\text{OH})_{24}^{7+}\) [16]. Although laboratory experiments have confirmed the existence of polynuclear \(\text{Al}_{13}\), there is doubt that “giant” cations such as \(\text{Al}_{13}\text{O}_{4}(\text{OH})_{24}^{7+}\) exist in nature [17]. However, under acidic RO feed conditions (pH ~5.5–6.5) that are often set for control of calcium carbonate scaling [16,18], the major aluminum species are \(\text{Al}^{3+}, \text{Al(SO}_4)_2^{6+}, \text{Al(OH)}^{3+}, \text{Al(OH)}_2^{2+}, \text{Al(OH)}_3^{+}\), and \(\text{Al(SO}_4)_2^{1-}\).

In the presence of silica, scaling due to aluminum silicates can also occur and antiscalants designed to control for silica scaling have often been reported to be ineffective for suppressing precipitation of aluminum silicates [19,20]. It has also been suggested that phosphorous (a key inorganic component in some antiscalant formulations) can react with aluminum [15].

In RO membrane desalting, \(\text{Al}^{3+}\) (as well as all other rejected mineral salt ions) in the retentate stream would be concentrated by a factor (CF) as given by the following equation:

\[
CF = \frac{C_c}{C_F} = \left(\frac{1}{1 - R_w (1 - R_s)}\right)
\]

in which \(C_c\) and \(C_F\) are the retentate and feed concentrations, respectively; \(R_s\) is the fractional salt rejection \((R_s = 1 - C_P/C_F)\) where \(C_P\) is the permeate concentration); and \(R_w\) is the fractional product water recovery \((R_w = Q_P/Q_F)\) where \(Q_P\) and \(Q_F\) are the permeate and feed flow rates, respectively. As an example, according to Eq. (1), the residual total \(\text{Al}^{3+}\) concentration in the retentate at product water recovery of 90% (often the target for high recovery brackish water desalting [21–23]) and salt rejection of 95% would increase by a factor (CF) of 9.5 relative to the RO feed concentration. Accordingly, total \(\text{Al}^{3+}\) concentration (both dissolved and colloidal forms) in the feed would increase, thereby raising the potential for adverse impact of aluminum on membrane scaling.

Indeed, recent pilot and laboratory tests with brackish feed water treated by conventional treatment have confirmed the presence of trace aluminum on scaled membrane surfaces [24,25]. In addition, a major concern is the potential adverse impact of aluminum on antiscalants effectiveness [26]. Therefore, there is a need to assess antiscalant performance and to evaluate the required dose in the presence of aluminum to overcome the adverse impact of aluminum on membrane scaling.

In the present study a systematic diagnostic approach has been developed for quantitative assessment and ranking of the impact of trace aluminum on antiscalant effectiveness in retarding gypsum crystallization. The methodology consists of first ranking antiscalants based on their ability to retard bulk crystallization of gypsum from supersaturated solutions, as quantified by the observed crystallization induction time [27,28]. Subsequently, the candidate antiscalants are evaluated in membrane scaling tests in a diagnostic plate-and-frame RO cell [23,29].
2. Experimental

2.1. Materials and reagents

Calcium chloride (CaCl$_2$.2H$_2$O), sodium chloride (NaCl), magnesium sulfate (MgSO$_4$.7H$_2$O), anhydrous sodium sulfate (Na$_2$SO$_4$) and aluminum sulfate octadecahydrate (Al$_2$(SO$_4$)$_3$.18H$_2$O) were used for the preparation of various test solutions in deionized water (Milli-Q water system, Millipore, San Jose, CA). All inorganic chemicals were reagent grade (Fisher Scientific, Pittsburgh, PA). Ethylenediamine-tetraacetic acid (EDTA, Fisher Scientific, Pittsburgh, PA) was used as the cleaning agent for the crystallizer reactor components and the turbidity probe. Diagnostic membrane scaling tests were performed using the low-pressure LFC-1 RO membrane obtained from Hydranautics (Oceanside, CA). This membrane is reported to have a root-mean-square surface roughness of 65 nm [23] with a low biofouling propensity [18].

Five different commercial antiscalants were obtained from their respective suppliers (Table 1): denoted as AS1 (Vitec 2000), AS2 (Flocon 100), AS3 (Flocon 260), AS4 (Kochtreat Max), and AS5 (POC). It is noted that the content of “residual solids” (i.e., non-volatile material) for the different antiscalants varied significantly (14.2–39.1%, w/w). The residual solids (i.e., non-volatile) content for each antiscalant was determined by low-temperature evaporation (50°C) of 1 g of antiscalant solution until no weight loss was observed (Table 1). Clearly, if the active ingredients were contained in the residual solids, then comparison of antiscalant effectiveness would have to be expressed on a mass basis. Unfortunately, the amount and/or precise identity of the active ingredients in commercial antiscalant formulations are proprietary. Therefore, in the present study antiscalants were compared at a dose level based on the experimentally determined mass of residual solids of the supplied formulations.

2.2. Bulk crystallization

Bulk crystallization induction times were determined following the method of Shih et al. [27] in a well-mixed 600 ml crystallization reactor (Fig. 1). Mixing was accomplished using a stirring plate (1150049S, Fisher Scientific, Pittsburgh, PA) and a 2" octagonal Teflon-coated magnetic stir bar with the rpm measured using a laser stroboscope (Extech 461825, Extech Instruments, Waltham, MA). Turbidity was monitored with a back-light scattering turbidity probe (Analite 90°) along with a turbidity meter (Analite 160) (McVan Instruments, Mulgrave, Australia). Continuous on-line measurements of solution turbidity in the stirred crystallization

<table>
<thead>
<tr>
<th>Antiscalant</th>
<th>Measured residual solids content (% wt)</th>
<th>Manufacturer</th>
<th>Reported active ingredients</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS1</td>
<td>28.1</td>
<td>Avista Technologies</td>
<td>Phosphino carboxylic acid polymer</td>
</tr>
<tr>
<td>AS2</td>
<td>39.1</td>
<td>Biolab Water Additives</td>
<td>Polyaacrylic acid</td>
</tr>
<tr>
<td>AS3</td>
<td>35.2</td>
<td>Biolab Water Additives</td>
<td>Aq. Solution containing polycarboxylic acid</td>
</tr>
<tr>
<td>AS4</td>
<td>15.8</td>
<td>Koch Membrane Systems</td>
<td>N/A</td>
</tr>
<tr>
<td>AS5</td>
<td>41.2</td>
<td>Degussa</td>
<td>Polycarboxylic acid</td>
</tr>
</tbody>
</table>
reactor served to signal the onset of crystallization. Response time for the turbidity probe was essentially instantaneous, allowing accurate determination of observed crystallization induction times even for the shortest induction times of several seconds. Reproducibility errors for measured induction times were in the range of ±5%.

### 2.3. Relative effectiveness of antiscalants

The impact of aluminum on antiscalant effectiveness was evaluated for an aluminum concentration range of 25 to 100 µg/L, which corresponds to the range of increase in Al concentration observed in recent studies of primary RO desalination of Colorado River water [24]. Crystallization experiments, with and without antiscalant addition, were carried out with model solutions prepared from reagent-grade chemicals dissolved in de-ionized water (Table 2). Bicarbonate, trace metals (e.g., barium) and natural organic matter were excluded to avoid coprecipitation of calcite and other mineral salts with gypsum during the diagnostic membrane scaling experiments. Sodium and chloride concentrations in the reference solution were adjusted to ensure a charge balance. Although gypsum precipitation is insensitive to pH [25,27,30], the crystallization tests were carried out at pH ~5.6, which is the pH level at which calcium carbonate scaling can be completely avoided.

<table>
<thead>
<tr>
<th>Ions</th>
<th>Composition of Solution A used in bulk gypsum crystallization studies mg/L (M)</th>
<th>Composition of Solution B used in gypsum scaling studies mg/L (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>2076 (0.1175 M)</td>
<td>664 (0.0289 M)</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>2050 (0.0513 M)</td>
<td>656 (0.0164 M)</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>800 (0.0328 M)</td>
<td>256 (0.0105 M)</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>3626 (0.1025 M)</td>
<td>1160 (0.0327 M)</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>7500 (0.0775 M)</td>
<td>2400 (0.0250 M)</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>16052</td>
<td>5136</td>
</tr>
<tr>
<td>pH</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>SI₉</td>
<td>4.09</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Thermodynamic solubility calculations using the OLI analyzer [31] suggest that at the above pH for the present range of total Al³⁺ concentration of 25 to 100 µg/L, only 4–17% of the aluminum is present in soluble form (major dissolved species are AlOH²⁺, Al(OH)₃⁺, Al(SO₄)⁺, and Al(SO₄)²⁻, with Al(OH)₃ being the predominant insoluble colloidal species.

The degree of supersaturation of the model feed solution with respect to gypsum was quantified in terms of the gypsum Saturation Index ($SI_g$), defined as:

$$SI_g = \frac{[Ca^{2+}] [SO_4^{2-}]}{K_{sp}}$$

where [Ca²⁺] and [SO₄²⁻] are the activities of the calcium and sulfate ions, respectively, and $K_{sp}$ is the solubility constant (product) for gypsum. The $SI_g$ was determined via multi-electrolyte thermodynamic solubility calculations using OLI Analyzer software. For model solutions A and B (Table 2), the $SI_g$s were 4.09 and 1.01, respectively. Bulk crystallization tests were conducted
with solution A for which the crystallization induction time was 0.42 h. Membrane scaling tests were carried out using solution B at just slightly above saturation in order to favor surface crystallization while avoiding bulk crystallization over the course of the 24-h scaling runs [23].

Prior to each experiment, the turbidity probe was thoroughly cleaned in a sonicator with a 0.03M EDTA solution at pH 11 for a period of 0.5 h. Once the solution was added to the crystallization vessel, the turbidity probe was then carefully and centrally aligned in the crystallization reactor. Predetermined volumes from stock solutions containing the antiscalant and aluminum were subsequently introduced to the crystallizing solution mixture exactly 1 min after the addition of the test solution. The rotational speed of the magnetic stirrer was then adjusted to 800 rpm, data acquisition was initialized and the system (crystallizer and turbidity probe) was covered with a black box to eliminate stray light. The test was terminated once the turbidity reached 1000 NTU. The observed induction time, $t_{\text{ind}}$, was estimated from the turbidity-time curve by fitting a straight line to the linear portion of the rapid crystallization region, and further extrapolating that line to the time axis. The point of intersection thereby designating the observed induction time [27].

2.4. Gypsum membrane scaling experiments

Membrane scaling experiments were conducted using a laboratory plate-and-frame RO membrane system (Fig. 2). This unit consists of two test cells arranged in parallel, each cell with membrane surface area of 19.76 cm² (2.6 cm × 7.6 cm) with a channel height of 2.66 mm. The feed reservoir was a magnetically stirred 18 L polyethylene tank with a refrigerated recirculator (model 625, Fisher Scientific, Pittsburgh, PA) that served to maintain a constant reservoir temperature. Feed was pumped to the RO module using a positive displacement pump (Hydra-Cell, Wanner Engineering, Minneapolis, MN) capable of delivering up to $6.94 \times 10^{-3}$ m³/s of feed solution. Transmembrane pressure was adjusted using a back-pressure regulator (US Paraplate, Auburn, CA) and a digital flow meter (model 1000, Fisher Scientific, Pittsburgh, PA), interfaced with a PC, provided for continuous monitoring of permeate flux and accumulated volume of product water. Permeate conductivity was monitored using a conductivity meter (model WD-35607-30, Oakton Research, Vernon Hills, IL). As a precautionary measure, a cartridge filter (0.45 µm; Flotex PN pleated filter, Osmonics, Minnetonka, MN) was installed at the retentate side of the membrane modules to trap bulk formed crystals and thus prevent the build-up of bulk crystals in the feed reservoir. This operational mode ensured that membrane scaling was dominated by surface crystallization [23].

Membrane scaling tests were carried out with a feed solution B set at $S_{I_g} = 1.01$ (Table 2). This solution was at the concentration level with respect to gypsum as expected for primary RO concentrate generated from CR water desalting at 85% recovery [21]. All scaling tests were conducted at a total recycle mode, thereby ensuring that the feed solution remained essentially at a constant concentration, given the negligible loss of calcium and sulfate ions due to bulk and surface crystallization. Prior to each scaling experiment, the membranes sheets were equilibrated in the RO cells, for a period of about 2 h by recirculating water through the system at a crossflow velocity of 0.11 m/s and permeate flow rate of about 3.1 mL/min, followed by the addition of model solution B (without calcium) for another 2 h equilibration also at a crossflow velocity of 0.11 m/s and permeate flow rate of 2.4 mL/min to establish a baseline for permeate flux. Subsequently, calcium chloride solution was added to the feed reservoir to initiate the membrane scaling experiment. The antiscalant and aluminum were added to the feed from their respective stock solutions, 10 and 5 min, respectively, prior to
the addition of the calcium chloride solution. After the completion of each scaling run (24 h), the membranes were removed from the cells and stored dry for subsequent imaging and determination of the extent of surface coverage by gypsum scale [23,30].

All membrane-scaling runs were carried out at the same crossflow velocity of 0.11 m/s and initial permeate flow rate of 2.25 mL/min, which was set by appropriately adjusting the transmembrane pressure. Thus, all scaling tests were conducted at the same initial level of concentration polarization at the membrane surface. Due to concentration polarization, solution supersaturation with respect to gypsum will be higher near the membrane surface relative to the feed solution. The average initial gypsum saturation index ($SI_{g0}$) along the membrane surface at the beginning of each run (i.e., $t = 0$), was determined to be 2.46, based on the estimated solution concentration at the membrane surface (i.e., $C_m = CP \cdot C_f$ where the degree of concentration polarization, $CP$, of 1.85 was estimated from the simple film model [23]).

3. Results and discussion

3.1. Homogeneous crystallization with aluminum and antiscalants

Crystallization induction time for gypsum precipitation based on solution A ($SI_g = 4.09$, Table 2) was 25 min as determined from turbidity measurements (Fig. 3). Upon the addition of
3 ppm of antiscalant, the onset of crystallization was prolonged as quantified by longer induction times (Fig. 3, Table 3). The gypsum crystallization suppression capability of the five antiscalants studied varied considerably as illustrated by the turbidity-time curves shown in Fig. 3. In terms of gypsum scale suppression effectiveness, the order followed AS2 > AS3 > AS5 > AS1 > AS4.

The relative impact of Al\(^{3+}\) on antiscalant effectiveness for total Al\(^{3+}\) concentration in the range of 25 to 100 µg/L was evaluated for the five antiscalants (Table 3) at an antiscalant dose of 3 ppm. In all cases, the onset of gypsum crystallization for the supersaturated model solution (\(SI_g = 4.09\)) was accelerated upon the addition of aluminum (Fig. 4a–e). The turbidity curves (Fig. 4a–e) demonstrate that the presence of aluminum reduced antiscalant effectiveness as quantified by the decrease of the crystallization induction times listed in Table 3. The ranking of antiscalants effectiveness, in the presence of aluminum, was AS2 > AS3 > AS4 > AS5 > AS1. It is noted that with increased antiscalant effectiveness (both in the absence or presence of aluminum), the region of slow turbidity rise (Figs. 3, 4 and 6) is more extended and at higher turbidity suggesting a measurable presence of antiscalant-bound crystals and/or nuclei prior to the onset of rapid crystallization [27].

The degree by which Al\(^{3+}\) reduced antiscalant effectiveness varied significantly among the different formulations. For example, in the presence of 25 µg/L total Al\(^{3+}\) the induction time decreased by up to about a factor of two relative to the aluminum-free solution. The lowest ranked antiscalant (AS4) at the above aluminum concentration was also least affected by aluminum displaying about 10% decrease in the crystallization induction time, relative to the aluminum-free case, and about a 34% decrease as the aluminum concentration increased.

### Table 3

<table>
<thead>
<tr>
<th>Al(^{3+}) (µg/L)</th>
<th>AS1 (min)</th>
<th>AS2 (min)</th>
<th>AS3 (min)</th>
<th>AS4 (min)</th>
<th>AS5 (min)</th>
</tr>
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<tbody>
<tr>
<td>100</td>
<td>30</td>
<td>110</td>
<td>120</td>
<td>92</td>
<td>60</td>
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<td>75</td>
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<td>510</td>
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<td>305</td>
<td>1690</td>
<td>1600</td>
<td>430</td>
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<tr>
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<td>2030</td>
<td>480</td>
<td>1100</td>
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<tr>
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<td>668</td>
<td>3693</td>
<td>2137</td>
<td>575</td>
<td>832</td>
</tr>
<tr>
<td>B</td>
<td>0.0313</td>
<td>0.0352</td>
<td>0.0315</td>
<td>0.0179</td>
<td>0.0298</td>
</tr>
</tbody>
</table>

\(^{a}\)Solution composition set at \(SI_g = 4.09\) (Table 2).

\(^{b}\)ln \((t_{ind,i}) = A_i - B_i C_{Al}\).
Fig. 4. Effect of different aluminum concentrations on antiscalant effectiveness for crystallization suppression. (a) AS1, (b) AS2, (c) AS3, (d) AS4, (e) AS5 (supersaturated solution A, $S_{lg} = 4.09$).

concentration increased from 25 to 50 µg/L. It is noted that, at the highest aluminum concentration of 100 µg/L, antiscalant AS1 was least effective with a gypsum precipitation induction time of 30 min relative to 25 min for the antiscalant and aluminum-free diagnostic solution. This behavior suggests that, at the above high aluminum concentration, the capacity of AS1 for binding gypsum nuclei and/or adsorbing onto crystal faces was completely consumed by the Al$^{3+}$ ions.

The crystallization induction time for gypsum, $t_{ind}$, correlated with total Al$^{3+}$ concentration, $C_{Al}$, as shown in Fig. 5. A log-linear correlation was observed of the form $\ln(t_{ind}) = \ln A_i - B_i C_{Al}$, in which $A_i$ and $B_i$ are empirical parameters unique for the specific antiscalant and RO feed source under consideration (Table 3). The above correlation indicates an exponential decay of the induction time with increased aluminum concentration. Clearly, aluminum has a marked adverse effect on antiscalant effectiveness. However, loss of antiscalant effectiveness can be alleviated, to some extent, by increasing the antiscalant dose, albeit this would be at an increased material (i.e., antiscalant) cost.

It is hypothesized that Al$^{3+}$ in solution competes with calcium ions (Ca$^{2+}$) for association
with the active constituents of the antiscalant formulations. Therefore, it would be reasonable to expect that by increasing the antiscalant dosage the threshold capacity of the antiscalant for suppressing gypsum crystallization would be increased. Accordingly, at a sufficiently high antiscalant dose, it should be possible to overcome the adverse impact of aluminum. As an example, by doubling the dose of AS1 from 3 ppm to 6 ppm, the induction time for the diagnostic solution ($SI_g = 4.09$) containing 100 µg/L Al$^{3+}$ increased from 30 min to 1000 min (Fig. 6a). Similarly, upon increasing antiscalant AS2 dosage from 3 ppm to 6 ppm, the crystallization induction time for the diagnostic solution ($SI_g = 4.09$ with 100 µg/L Al$^{3+}$) increased from 110 min to 3700 min (Fig. 6b and Table 3).

3.2. Membrane scaling experiments with aluminum and antiscalants

Membrane mineral salt scaling is known to occur at lower supersaturation levels compared to homogeneous (i.e., bulk) crystallization due to the presence of a heterogeneous membrane surface [13,30,32–36]. However, it is expected that the relative trend of antiscalant effectiveness and the impact of trace levels of aluminum should be similar for both bulk and heterogeneous crystallization (e.g., at the membrane surface). In order to verify the above hypothesis, a series of membrane scaling experiments were carried out with a model solution ($SI_g = 1.01$) for an aluminum concentration of 100 µg/L using the highest ranked (AS2) and lowest ranked (AS1) antiscalants (see Table 3). The feed solution was just slightly above supersaturation with respect to gypsum ($SI_g = 1.01$), thereby avoiding bulk crystallization in the feed reservoir and system lines over the course of the 24-h scaling test (see Section 2.4). For the present operating conditions, the average initial gypsum saturation index at the membrane surface was 2.20.
In the absence of Al$^{3+}$ and antiscalant addition, flux decline for the test membrane reached about 30% at the end of the 24-h test period (Fig. 7). Image analysis of the scaled membranes [22,23] revealed about 27% surface coverage by gypsum scale, which was consistent with the degree of flux decline. Flux decline was dramatically reduced to about 3.5% and 1.5% upon the addition of 3 ppm AS1 and AS2 (Fig. 7), respectively, to the diagnostic solution with no observable scale on the membrane surface (Fig. 8). It is noted that the slight flux decline of about 3% is expected [22], prior to the introduction of the scaling solution, due to membrane equilibration. Therefore, it is reasonable to conclude that gypsum scale formation was virtually eliminated for a 3 ppm dose of either the AS1 or AS2 antiscalants. The presence of 100 µg/L Al$^{3+}$ in the feed solution decreased antiscalant effectiveness and flux decline reached about 11% and 5.7% with antiscalants AS1 and AS2 (both at 3 ppm dosage), respectively, at the end of the 24-h scaling test (Fig. 7), with corresponding 6.5% of the membrane area covered by gypsum scale (Fig. 8) for AS1 and virtually no scale coverage for AS2.
Conditions that resulted in a greater decrease in antiscalant effectiveness in bulk crystallization tests (i.e., higher $\text{Al}^{3+}$ concentration and lower antiscalant dose) also resulted in greater degree of flux decline due to scaling and correspondingly higher fraction of surface scale coverage. Both bulk crystallization and membrane scaling tests confirmed the greater effectiveness of antiscalant AS2 relative to AS1 for suppressing gypsum scale both in the presence and absence of aluminum. It is important to recognize that the relative performance of the antiscalants as quantified by both flux decline and scale surface coverage is in agreement with the trend observed in the bulk crystallization tests (Table 3). The above results suggest that bulk crystallization tests can provide information on the relative effectiveness of antiscalants for specific water chemistries. Such information can be particularly useful in narrowing the selection of candidate antiscalants for detailed evaluation in membrane scaling diagnostic tests prior to pilot plant studies.

4. Conclusions

The present study showed that both bulk crystallization along with diagnostic membrane scaling tests can be used for rapid ranking and selection of antiscalants. An additional outcome is a quick method for the determination of the optimal antiscalant dose. Studies with source water containing $\text{Al}^{3+}$ demonstrated a reduction in antiscalant effectiveness for suppression of gypsum crystallization. Ranking of five different commercial antiscalants for gypsum scale suppression revealed significant performance differences among the antiscalants. It was shown via both crystallization induction time and membrane scaling tests that the adverse impact of $\text{Al}^{3+}$ can be overcome by increasing antiscalant dose, although this would increase the RO process chemical treatment cost. Membrane scaling experiments confirmed that ranking of antiscalant effectiveness and impact of $\text{Al}^{3+}$, based on flux decline and surface scale coverage, correlated with ranking obtained from the bulk solution crystallization test. It is suggested that the above approach can be valuable in identifying effective candidate antiscalants, thereby assisting in the design and optimization of field pilot membrane studies.

Acknowledgements

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References


