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## Synthesis of polyaspartic acid-capped 2-aminoethylamino acid as a green water treatment agent and study of its inhibition performance and mechanism for calcium scales†

 Yong-Hong Cai,<sup>a</sup> Jia-Li Zhao,<sup>a</sup> Xin-Yu Guo,<sup>ab</sup> Xiao-Juan Zhang,<sup>a</sup> Ran-Ran Zhang,<sup>a</sup> Shao-Rong Ma,<sup>a</sup> Ya-Min Cheng,<sup>ID \*a</sup> Zhong-Yan Cao,<sup>ID \*a</sup> and Ying Xu,<sup>ID \*abc</sup>

Polyaspartic acid (PASP), a well-known green scale inhibitor for industrial water treatment, might be decomposed with prolonged duration, and its anti-scaling performance against  $\text{CaCO}_3$  and  $\text{CaSO}_4$  is diminished at a low concentration ( $<10 \text{ mg L}^{-1}$ ) and a high temperature. With semi-ethylenediaminetetraacetic acid (EDTA) tetrasodium salt as the mimicking model, novel phosphorus-free PASP-capped 2-aminoethylamino acid (PASP-ED<sub>2</sub>A) containing side chains bearing multi-functional groups is rationally designed and successfully prepared *via* the ring-opening reaction of cheap poly(succinimide) under mild reaction conditions with the assistance of readily available 2-aminoethyl amino acid. The static scale inhibition method is used to evaluate the scale inhibition performance of the as-synthesized PASP derivative. Scanning electron microscopy, X-ray diffraction, and X-ray photoelectron spectroscopy are utilized to monitor the crystallization process of calcium carbonate and calcium sulfate scales, and density functional theory calculations are conducted to shed light on the relationship between the molecular structure and scale inhibition mechanism of PASP-ED<sub>2</sub>A. Results show that the as-prepared PASP-ED<sub>2</sub>A shows better scale inhibition performance for  $\text{CaCO}_3$  and  $\text{CaSO}_4$  than PASP with a low concentration, a high temperature, and an extended duration. Particularly, PASP-ED<sub>2</sub>A with a concentration of  $10 \text{ mg L}^{-1}$  exhibits the best scale inhibition performance for  $\text{CaCO}_3$ ; its scale inhibition capacity is about two times as much as that of PASP. The reason lies in that the coordination atoms in the molecular structure of PASP-ED<sub>2</sub>A can chelate with  $\text{Ca}^{2+}$  to inhibit the combination of  $\text{Ca}^{2+}$  with anions and prevent the generation of  $\text{CaCO}_3$  and  $\text{CaSO}_4$  scales. The PASP-ED<sub>2</sub>A derivative can more efficiently retard the formation and growth of  $\text{CaCO}_3$  and  $\text{CaSO}_4$  crystal nuclei and exerts better inhibition performance against  $\text{CaCO}_3$  and  $\text{CaSO}_4$  scales than PASP.

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### 1. Introduction

With the rapid development of industry and the increase of water consumption,<sup>1</sup> water recycling has become an important means to save water resources. Reports demonstrate that industrially circulated cooling water accounts for 70–90% of the total industrial water consumption.<sup>2</sup> However, the repeatedly used cooling water often contains increased contents of calcium and magnesium ions and is hence liable to scaling.<sup>3,4</sup> This will not only cause the clogging and corrosion of heat exchange and

production equipment but also reduce the heat transfer rate of the equipment, thereby adding to the production cost.<sup>5–9</sup> Therefore, some researchers developed several techniques for inhibiting or remediating the scale formation and found that scale inhibitors could be of special significance in this respect.<sup>10–13</sup> Among various scale inhibitors, polyaspartic acid (PASP) could be the most promising one, since it is cheap, non-toxic, phosphorous-free and biodegradable.<sup>14–18</sup> Nevertheless, it exhibits relatively poor scale inhibition performance at a low concentration or high temperature over a prolonged duration, which limits its practical application in industry.<sup>19</sup> In this sense, it is imperative to design and synthesize phosphorus-free PASP derivatives with desired antiscale performance under mild reaction condition. Two major strategies are currently available for that purpose. One is the copolymerization of L-aspartic acid, and another is the amino ring-opening modification of poly-succinimide (PSI). Both strategies afford functionalized PASP

<sup>a</sup>College of Chemistry and Chemical Engineering, Henan University, Kaifeng 475004, China. E-mail: chengyamin@henu.edu.cn; zycao@henu.edu.cn; hdccxu@126.com

<sup>b</sup>Engineering Research Center for Water Environment and Health of Henan, Zhengzhou University of Industrial Technology, Zhengzhou 451150, China

<sup>c</sup>Central Philippine University, Iloilo 5003, Philippines

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with improved antiscalting efficiency, thanks to the introduction of the side chains bearing functional groups (e.g., sulfonic ( $-\text{SO}_3\text{H}$ ), carboxylic ( $-\text{CO}_2\text{H}$ ), hydroxyl ( $-\text{OH}$ ), and amino ( $-\text{NR}_2$ )) that can be coordinated with  $\text{Ca}^{2+}$  (Scheme 1).<sup>20–22</sup>

In practice, however, high concentrations of PASP derivatives are often necessary in order to achieve a satisfactory scale inhibition effect. Viewing that polymers with high chelation ability with  $\text{Ca}^{2+}$  might contribute to enhancing the antiscalting performance, we envision the selective installation of side chains bearing polydentate coordination groups (carboxylic, amino, acylamido, etc.) might provide a new solution to further improve the scale inhibition performance. Since ethylenediaminetetraacetic acid (EDTA) tetrasodium salt is a very good chelating agent widely used for the quantitative detection of  $\text{Ca}^{2+}$ , we anticipate that the installation of semi-EDTA to the side chain of the PASP derivative could provide novel antiscalting agents with greatly improved antiscaling performance. With our continuing interest in this area, in the present research we prepare a PASP derivative bearing side chain containing multi-functional group (phosphorus-free PASP-capped 2-aminoethyl amino acid (denoted as PASP-ED<sub>2</sub>A)) by mimicking semi-EDTA under mild reaction condition (Scheme 1). This paper evaluates the scale inhibition performance of the as-synthesized PASP derivative by static scale inhibition method and observes the crystallization process of calcium scale by means of scanning electron microscopy, X-ray diffraction, and X-ray photoelectron spectroscopy. Besides, it aims at shedding light on the plausible scale inhibition mechanism of the PASP derivative based on density functional theory (DFT) calculations.

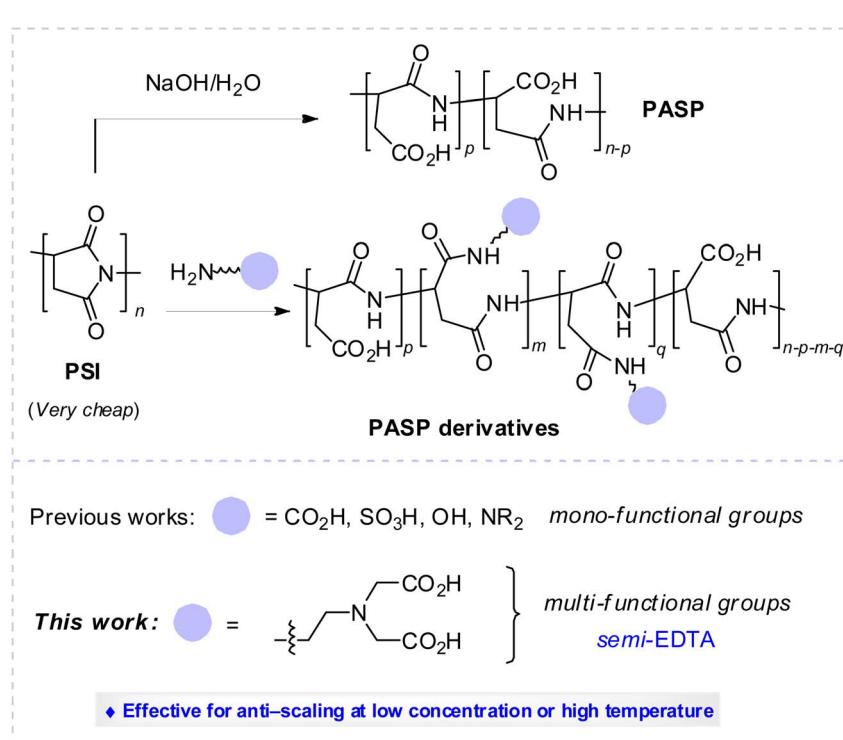
## 2. Materials and methods

### 2.1 Materials

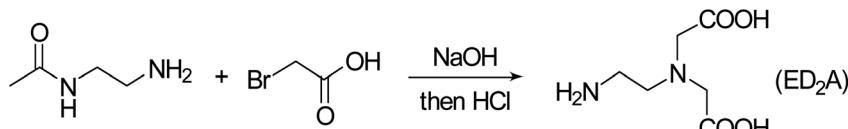
Analytical reagents (AR) bromoacetic acid and ethylenediamine as well as industrial grade PSI ( $M_w = 7000$ ) were provided by Shanghai Aladdin Biochemical Technology Company Limited (Shanghai, China). *N*-Acetylenediamine was purchased from Shanghai Shaoyuan Regent Company Limited (Shanghai, China). Anhydrous sodium sulfate (AR), ethylenediaminetetraacetic acid disodium salt (AR), anhydrous calcium chloride (AR), borax (AR) and potassium hydroxide (AR) were provided by Tianjin Kermel Chemical Reagent Company Limited (Tianjin, China). Anhydrous sodium bicarbonate (AR) was purchased from Tianjin Deen Chemical Regent Company Limited (Tianjin, China). Anhydrous ethanol (AR) was obtained from Anhui Ante Food Company Limited (Suzhou, China). Deionized water (DI) prepared at our laboratory was used as the solvent and for rinsing as well.

### 2.2 Synthesis of 2,2'-(2-aminoethyl)azanediyi diacetic acid-polyaspartic acid (PASP-ED<sub>2</sub>A)

Certain amounts of *N*-acetylenediamine, bromoacetic acid and distilled water were placed in a 50 mL round bottom flask while a proper amount of sodium hydroxide solution (8 mol L<sup>-1</sup>) was dropwise added. The resultant solution was held at ambient condition for 3 days, followed by the addition of a proper amount of sodium hydroxide solution (5 mol L<sup>-1</sup>) and further reaction for additional 3 days. Upon completion of reaction, hydrochloric acid (5 mol L<sup>-1</sup>) was added to adjust the solution pH to about 8 thereby affording ED<sub>2</sub>A (Fig. 1).<sup>23</sup>



Scheme 1 Synthesis of PASP derivative by ring-opening reaction of polysuccinimide.

Fig. 1 Synthesis route of ED<sub>2</sub>A.

Certain amounts of the aqueous solutions of PSI, ED<sub>2</sub>A and sodium hydroxide were placed in a 50 mL round bottom flask and stirred at 60 °C for 24 h in a water bath. At the end of reaction, the solution was poured in anhydrous ethanol to allow sedimentation, followed by holding at ambient condition as well as filtration and drying of the lower precipitate to obtain the crude product. The crude product was purified with a dialysis bag and then steamed to obtain a yellow solid, the target product PASP-ED<sub>2</sub>A with 53% yield (Fig. 2). Noteworthy, although seven days and extra industrial raw chemical reagents (such as ethylenediamine and bromoacetic acid) was needed to synthesis PASP-ED<sub>2</sub>A than that of PASP, the safe and easy-to-handle nature, as well as its better antiscaling performance makes it worth to do.

### 2.3 Characterization of PASP and PASP-ED<sub>2</sub>A

The structure of PASP and PASP-ED<sub>2</sub>A was characterized by Fourier transform infrared spectroscopy (VERTEX 70 FTIR spectrometer, Bruker Optics, Germany) and <sup>1</sup>H nuclear magnetic resonance spectroscopy (<sup>1</sup>H NMR; AVANCE 400 MHz NMR spectrometer, Bruker Optics, Germany).

### 2.4 Static scale inhibition tests

**2.4.1 Static scale inhibition efficiency against CaCO<sub>3</sub>.** The static scale inhibition method was used to determine the scale inhibition performance of the as-synthesized PASP-ED<sub>2</sub>A derivative as water treatment agent. The test solution containing 240 mg L<sup>-1</sup> Ca<sup>2+</sup> and 732 mg L<sup>-1</sup> HCO<sub>3</sub><sup>-</sup> was prepared and heated at 80 °C for 10 h in a water bath. At the end of heating, the solution was naturally cooled to room temperature. The concentration of Ca<sup>2+</sup> in the supernatant is determined by EDTA titration. The scale inhibition rate for CaCO<sub>3</sub> is calculated by formula (1):

$$\eta = \frac{C_2 - C_1}{C_0 - C_1} \times 100\% \quad (1)$$

where  $C_0$  is the concentration of Ca<sup>2+</sup> (mg L<sup>-1</sup>) in the solution before the experiment, and  $C_1$  and  $C_2$  are the concentrations of Ca<sup>2+</sup> (mg L<sup>-1</sup>) in the solutions after the experiments with and without PASP-ED<sub>2</sub>A derivative. All the static inhibition tests were conducted in triplicate to ensure reproducibility.

**2.4.2 Static scale inhibition efficiency against CaSO<sub>4</sub>.** The test solution containing 2000 mg L<sup>-1</sup> Ca<sup>2+</sup> and 4800 mg L<sup>-1</sup> SO<sub>4</sub><sup>2-</sup> was prepared and heated at 70 °C for 6 h in a water bath. At the end of heating, the solution was naturally cooled to room temperature. After filtration, the concentration of Ca<sup>2+</sup> in the supernatant is determined by EDTA titration. The scale inhibition rate for CaSO<sub>4</sub> is calculated by formula (2):

$$\eta = \frac{X_2 - X_1}{X_0 - X_1} \times 100\% \quad (2)$$

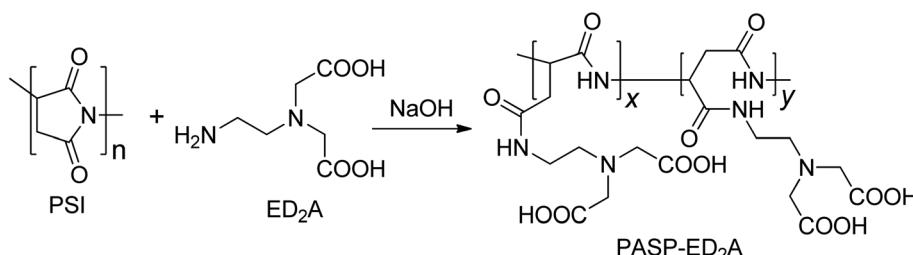
where  $X_0$  is the initial concentration of Ca<sup>2+</sup> (mg L<sup>-1</sup>) in the solution before heating; and  $X_2$  and  $X_1$  are the concentrations of Ca<sup>2+</sup> (mg L<sup>-1</sup>) after reaction in the presence and absence of the scale inhibitor. The static inhibition tests were repeated for three times; and the averages of the repeat tests were cited to minimize data scattering.

### 2.5 Surface analysis of scale crystal

A field emission scanning electron microscope (SEM, JSM-7610F, Japan Electronics Corporation) was used to observe the morphology of the scales. An X-ray powder diffractometer (XRD, D8 Advance, Bruker, Germany) was used to analyze the crystalline change of CaCO<sub>3</sub> scale and CaSO<sub>4</sub> scale. An X-ray photoelectron spectroscope (XPS, Thermo Scientific K-Alpha+, USA) was performed to explore the scale inhibition mechanism of PASP-ED<sub>2</sub>A derivative.

### 2.6 Monitoring crystallization process of calcium scale

The pH curve of CaCO<sub>3</sub> solution can reflect the scale inhibition performance of PASP-ED<sub>2</sub>A derivative to a certain extent.<sup>24</sup> Prior to the experiments, CaCl<sub>2</sub> solution and NaHCO<sub>3</sub> solution of an

Fig. 2 Synthesis route of PASP-ED<sub>2</sub>A derivative.

equal concentration were prepared. The as-obtained  $\text{CaCl}_2$  solution and  $\text{NaHCO}_3$  solution were then mixed at pre-set volume fractions to afford the to-be-tested  $\text{CaCO}_3$  solutions with concentrations of 0.015, 0.020, 0.025, and 0.030 mol  $\text{L}^{-1}$  (denoted as solutions A, B, C, and D). Before the  $\text{CaCl}_2$  solution and  $\text{NaHCO}_3$  solution were mixed, their pH was adjusted to 8.9 with NaOH solution while the scale inhibitor was added to the  $\text{NaHCO}_3$  solution in advance. The mixed solution was stirred at  $(25.0 \pm 0.1)^\circ\text{C}$  and its pH was recorded at pre-set time intervals. The time when the pH started to drop sharply is recorded as  $t_{\text{ind}}$ . According to the theory of classic homogeneous nucleation, the relationship between  $t_{\text{ind}}$  and  $\ln S$  can be obtained from eqn (3):<sup>25,26</sup>

$$\ln t_{\text{ind}} = B + \frac{\beta \gamma^3 V_m^2 N_A f(\theta)}{R^3 T^3 (\ln S)^2} \quad (3)$$

where  $B$  is the constant,  $\gamma$  is the surface energy of calcium carbonate or calcium sulfate crystal ( $\text{J m}^{-2}$ ),  $\beta$  is the geometric (shape) factor of  $16\pi/3$  for the spherical nucleus,  $f(\theta)$  is the correction factor (1.0 for homogeneous nucleation and  $<1.0$  for heterogeneous nucleation),<sup>25,28</sup>  $V_m$  is the molar volume of the phase forming ( $36.93 \text{ cm}^3 \text{ mol}^{-1}$  for  $\text{CaCO}_3$  and  $74.69 \text{ cm}^3 \text{ mol}^{-1}$  for  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ),<sup>25</sup>  $N_A$  is Avogadro's number,  $R$  is the gas constant, and  $T$  is the absolute temperature.

Similarly, the conductivity test of  $\text{CaSO}_4$  solution can reflect the performance of the scale inhibitor to a certain extent. In this case,  $\text{CaCl}_2$  solution and  $\text{Na}_2\text{SO}_4$  solution with the same concentration were prepared in advance; and they were then mixed at pre-set volume fractions to obtain  $\text{CaSO}_4$  solutions with concentrations of 0.07, 0.08, 0.09, and 0.10 mol  $\text{L}^{-1}$  (denoted as solutions A<sub>1</sub>, B<sub>1</sub>, C<sub>1</sub>, and D<sub>1</sub>). Before the  $\text{CaCl}_2$  solution and  $\text{Na}_2\text{SO}_4$  solution were mixed, their pH was adjusted to 8.9 with NaOH solution while the scale inhibitor was added to the  $\text{Na}_2\text{SO}_4$  solution in advance. The mixed solution was stirred at  $(25.0 \pm 0.1)^\circ\text{C}$ , and its conductivity was recorded at pre-set time intervals. The time when the conductivity started to drop sharply is recorded as  $t_{\text{ind}}$ . According to the theory of classic homogeneous nucleation, the relationship between  $t_{\text{ind}}$  and  $\ln S$  can also be expressed by eqn (3).<sup>26,27</sup>

For the pH test of calcium carbonate, the supersaturation ratio ( $S$ ) of the four tested solutions is 93.325, 144.544, 204.174, and 269.153, respectively, based on the calculation from Yang.<sup>29</sup> For the conductivity test of calcium sulfate, the supersaturation ratio ( $S$ ) of the four tested solutions is 5.248, 6.166, 7.079, and 8.128.

### 3. Results and discussion

#### 3.1 Structural characterization of PASP and PASP-ED<sub>2</sub>A

As shown in Fig. 3, the symmetric stretching vibration peaks of C–N bond and C=O bond in PSI are at  $1400 \text{ cm}^{-1}$  and  $1716 \text{ cm}^{-1}$ , respectively. PASP-ED<sub>2</sub>A shows the stretching vibration peaks of N–H, C=O and C–N in the amide bond at  $3393 \text{ cm}^{-1}$ ,  $1621 \text{ cm}^{-1}$  and  $1401 \text{ cm}^{-1}$ . Noticeably, the dramatic change of vibration peak of carbonyl group from  $1716 \text{ cm}^{-1}$  (with broad signal) can be attributed to the fact that

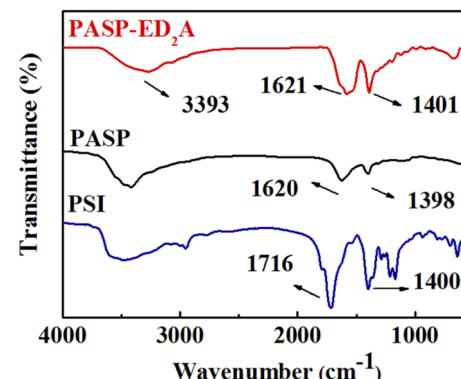


Fig. 3 FTIR spectra of PSI, PASP and PASP-ED<sub>2</sub>A.

the formation of extra amide bond *via* ring-opening aminolysis. This is very similar to PASP (with two dramatic peaks at  $1620$  and  $1398 \text{ cm}^{-1}$ ), indicating that PSI reacts with ED<sub>2</sub>A to generate PASP-ED<sub>2</sub>A.

Fig. 4 shows the <sup>1</sup>H NMR spectra of ED<sub>2</sub>A, PASP and PASP-ED<sub>2</sub>A in  $\text{D}_2\text{O}$ . The two absorbance peaks of  $-\text{CH}_2-$  in ED<sub>2</sub>A with an integration rate of 1 : 1 appear at 2.50 ppm and 3.10 ppm (Fig. 4(a)), which indicates that ED<sub>2</sub>A is successfully synthesized. As depicted in Fig. 4(b), the broad peaks of  $-\text{CH}-$  and  $-\text{CH}_2-$  of PASP molecular chain emerge at 2.60 ppm and 4.30 ppm (with an integration ratio of 2 : 1), respectively. Besides, aside from the  $-\text{CH}-$  and  $-\text{CH}_2-$  peaks of PASP, the as-synthesized PASP-ED<sub>2</sub>A shows the peaks of  $-\text{CH}_2-$  in ED<sub>2</sub>A at 3.50 ppm and 3.80 ppm (Fig. 4(c)). These data can further confirm the successful synthesis of PASP-ED<sub>2</sub>A derivative.

#### 3.2 Scale inhibition efficiency towards $\text{CaCO}_3$ and $\text{CaSO}_4$

Fig. 5(a) shows the scale inhibition efficiency-concentration curves of PASP and PASP-ED<sub>2</sub>A towards  $\text{CaCO}_3$ . In general, the scale inhibition efficiency of both scale inhibitors increases with the increase of their concentration and remains nearly unchanged at a certain concentration, showing an obvious “threshold effect”.<sup>30</sup> Particularly, PASP-ED<sub>2</sub>A exhibits better

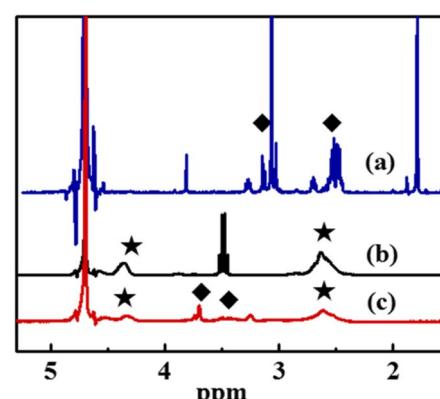


Fig. 4 <sup>1</sup>H NMR spectra of (a) ED<sub>2</sub>A, (b) PASP and (c) PASP-ED<sub>2</sub>A in  $\text{D}_2\text{O}$ .



scale inhibition performance against  $\text{CaCO}_3$  than PASP, especially at a low concentration of  $5 \text{ mg L}^{-1}$ . This indicates that the introduction of coordination group-containing species into the side chain of PASP molecule contributes to greatly improving its scale inhibition performance. The reason might lie in that the coordination atoms of PASP-ED<sub>2</sub>A molecule can chelate with free  $\text{Ca}^{2+}$  in water to inhibit its sedimentation therein.

Since the test temperature has an important influence on the scale inhibition performance of scale inhibitor,<sup>5,31,32</sup> the scale inhibition performance of PASP and PASP-ED<sub>2</sub>A is further evaluated in the test temperature range of  $40\text{--}80^\circ\text{C}$ . As can be seen from Fig. 5(b), the scale inhibition efficiency of PASP and PASP-ED<sub>2</sub>A towards  $\text{CaCO}_3$  decreases with the increase of temperature; and the scale inhibition efficiency of PASP-ED<sub>2</sub>A is higher than that of PASP in the whole temperature range. For example, the scale inhibition efficiency of PASP decreases from 75.3% to 49.0% as the test temperature rises from  $40^\circ\text{C}$  to  $80^\circ\text{C}$ . Differing from PASP, the as-synthesized PASP-ED<sub>2</sub>A maintains a high inhibition efficiency of 100% at  $40\text{--}50^\circ\text{C}$ , although the solubility of  $\text{CaCO}_3$  decreases with increasing temperature. Fig. 5(c) shows the inhibition efficiency-time curves of PASP and PASP-ED<sub>2</sub>A towards  $\text{CaCO}_3$  scale. The scale inhibition efficiency of PASP-ED<sub>2</sub>A decreases slowly with the extension of test time and is generally higher than that of PASP. Besides, PASP-ED<sub>2</sub>A retains a scale inhibition efficiency of 57.1% after 12 h of scale inhibition test, which indicates that PASP-ED<sub>2</sub>A has good time adaptability.

Fig. 6 shows the variations of the inhibition efficiency of PASP and PASP-ED<sub>2</sub>A towards  $\text{CaSO}_4$  scale with inhibitor

concentration as well as test temperature and time. As shown in Fig. 6(a), the scale inhibition efficiency of PASP and PASP-ED<sub>2</sub>A increases sharply with increasing inhibitor concentration in the range of  $1\text{--}6 \text{ mg L}^{-1}$ . This is because the increase of the inhibitor concentration refers to the increase of the amount of scale inhibition molecules in the solution and to the augmented coordination probability of  $\text{Ca}^{2+}$  by the inhibitor.

Fig. 6(b) shows the influence of test temperature on the scale inhibition efficiency. The scale inhibition efficiency of PASP and PASP-ED<sub>2</sub>A decreases significantly with the increase of temperature, which is because the crystallization rate of  $\text{CaSO}_4$  scale increases rapidly therewith; and PASP-ED<sub>2</sub>A exhibits a scale inhibition efficiency of 42.7% even at  $90^\circ\text{C}$ , much higher than that of PASP (only 24.2%).

Fig. 6(c) shows the variation of the inhibition efficiency of PASP-ED<sub>2</sub>A and PASP against  $\text{CaSO}_4$  scale with test time. With the extension of time, the scale inhibition efficiency of PASP gradually decreases, and the scale inhibition efficiency of PASP-ED<sub>2</sub>A still remains at 100% even after 24 h of inhibition test. This indicates that PASP-ED<sub>2</sub>A has excellent resistance against  $\text{CaSO}_4$  scale.

### 3.3 Characterization of $\text{CaCO}_3$ and $\text{CaSO}_4$ scales

The SEM images of  $\text{CaCO}_3$  crystals in the absence and presence of the scale inhibitors are shown in Fig. 7. In the absence of the scale inhibitors, the  $\text{CaCO}_3$  crystal exhibits a very regular cubic structure. After adding PASP, the crystal structure of  $\text{CaCO}_3$  is destroyed; and its surface morphology becomes irregular while

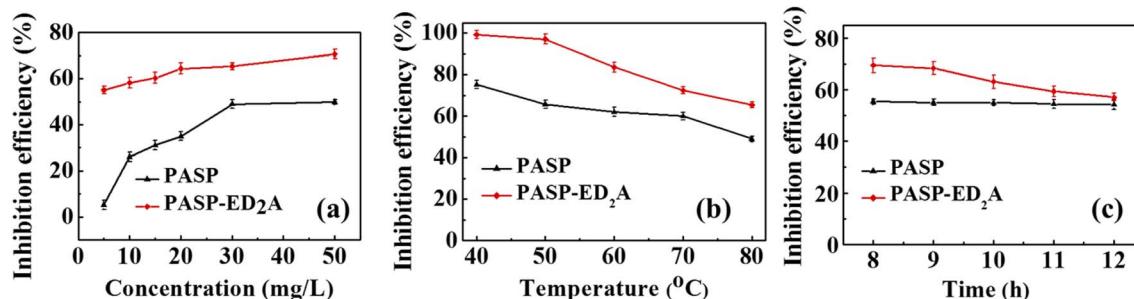


Fig. 5 Inhibition efficiency of PASP-ED<sub>2</sub>A and PASP towards  $\text{CaCO}_3$  scale versus (a) inhibitor concentration, (b) test temperature, and (c) test time.

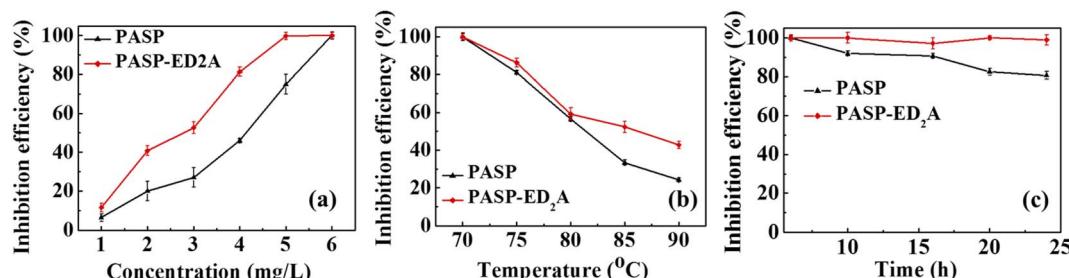


Fig. 6 Inhibition efficiency of PASP-ED<sub>2</sub>A and PASP towards  $\text{CaSO}_4$  scale versus (a) inhibitor concentration, (b) test temperature, and (c) test time.



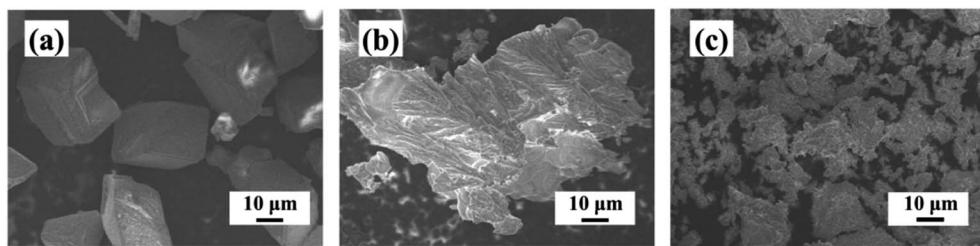


Fig. 7 SEM images of  $\text{CaCO}_3$ : (a) without scale inhibitor, (b) with  $30 \text{ mg L}^{-1}$  PASP, and (c) with  $30 \text{ mg L}^{-1}$  PASP- $\text{ED}_2\text{A}$ .

its structure becomes loose in association with the increase of particle size. After the addition of PASP- $\text{ED}_2\text{A}$ , the  $\text{CaCO}_3$  crystal appears as loose small particles with good access to dispersion. This could be because, on the one hand, the coordination groups in the molecular structure of PASP- $\text{ED}_2\text{A}$  can chelate with  $\text{Ca}^{2+}$ , thereby inhibiting the production of  $\text{CaCO}_3$  crystal. On the other hand, PASP- $\text{ED}_2\text{A}$  can be adsorbed on the surface of  $\text{CaCO}_3$  crystal, thereby inhibiting its regular growth and adding to its looseness. At the same time, the scale inhibitor molecules with negative charge adsorbed on the surface of  $\text{CaCO}_3$  crystal could contribute to preventing the aggregation of  $\text{CaCO}_3$  particles, thereby yielding  $\text{CaCO}_3$  crystal with a reduced size.

Fig. 8 shows the SEM images of  $\text{CaSO}_4$  scales in the absence and presence of the scale inhibitors. In the absence of the agent,  $\text{CaSO}_4$  scale crystal presents a typical rectangular and tetragonal

structure. After the addition of PASP, the surface of  $\text{CaSO}_4$  scale crystal becomes smooth. After the addition of PASP- $\text{ED}_2\text{A}$ ,  $\text{CaSO}_4$  scale crystals grow into short rods and the surface becomes very rough. This may be due to the adsorption of PASP- $\text{ED}_2\text{A}$  on the surface of scale crystal, which leads to the change of scale morphology.

The effect of the scale inhibitor on the crystal structure of  $\text{CaCO}_3$  and  $\text{CaSO}_4$  scales is investigated by XRD. Fig. 9(A) shows the XRD patterns of  $\text{CaCO}_3$  scale without and with the addition of PASP and PASP- $\text{ED}_2\text{A}$ . The  $\text{CaCO}_3$  scale formed in the absence of the scale inhibitors mainly consists of calcite and aragonite. After the addition of PASP, the characteristic diffraction peaks of vaterite appear, and those of aragonite almost disappear. This indicates that the  $\text{CaCO}_3$  scale formed in the presence of PASP mainly consists of calcite and vaterite. After the addition of PASP- $\text{ED}_2\text{A}$ , the characteristic diffraction

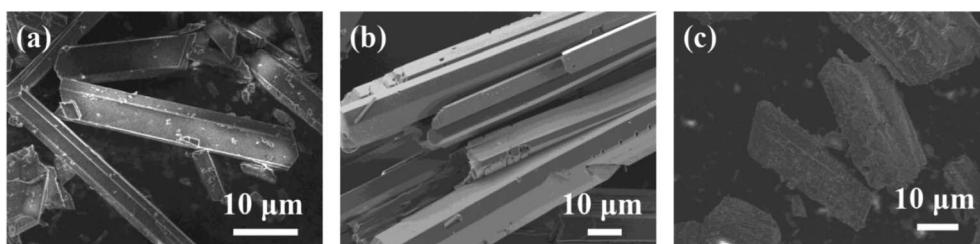


Fig. 8 SEM images of  $\text{CaSO}_4$ : (a) without the scale inhibitor, (b) with  $4 \text{ mg L}^{-1}$  PASP, and (c) with  $4 \text{ mg L}^{-1}$  PASP- $\text{ED}_2\text{A}$ .

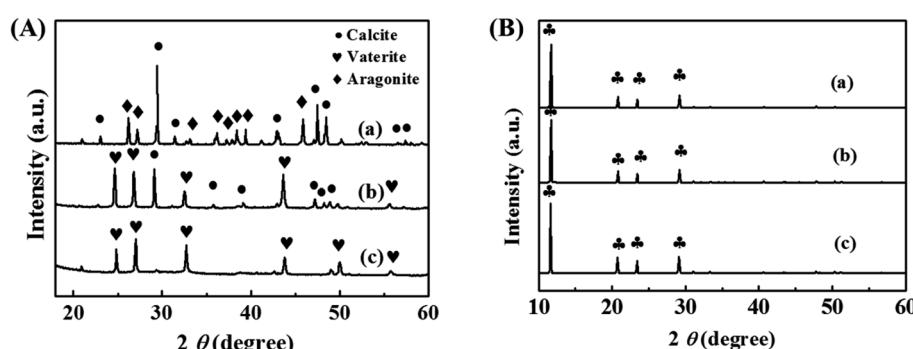


Fig. 9 XRD patterns of  $\text{CaCO}_3$  scales formed in (A) aqueous solution of  $\text{CaCO}_3$  ((a) without the scale inhibitor, (b) with  $30 \text{ mg L}^{-1}$  PASP, and (c) with  $30 \text{ mg L}^{-1}$  PASP- $\text{ED}_2\text{A}$ ) and (B) aqueous solution of  $\text{CaSO}_4$  ((a) without the scale inhibitor, (b) with  $4 \text{ mg L}^{-1}$  PASP, and (c) with  $4 \text{ mg L}^{-1}$  PASP- $\text{ED}_2\text{A}$ ).



peak of the (110) facet of calcite disappears completely, possibly because the PASP-ED<sub>2</sub>A molecules adsorbed on the surface of CaCO<sub>3</sub> particles *via* coordination contribute to effectively inhibiting the growth of CaCO<sub>3</sub> crystal along the (110) plane.<sup>5,33-35</sup> Therefore, the main configuration of calcium carbonate is vaterite after the addition of PASP-ED<sub>2</sub>A.

Fig. 9(B) shows the XRD patterns of CaSO<sub>4</sub> scale after adding PASP and PASP-ED<sub>2</sub>A. It can be seen that the main crystal type of CaSO<sub>4</sub> scale formed without the addition of the scale inhibitors is gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O); and the crystal pattern of CaSO<sub>4</sub> scale obtained after the addition of PASP and PASP-ED<sub>2</sub>A remains unchanged. This, in combination with corresponding SEM analysis, demonstrates that the scale inhibitor PASP-ED<sub>2</sub>A can change the surface morphology of CaSO<sub>4</sub> scale but has no influence on its crystal type.<sup>7,33,36,37</sup>

Fig. 10 shows the Ca 2p-XPS spectra of CaCO<sub>3</sub> scales obtained with and without the addition of the scale inhibitors. The addition of PASP and PASP-ED<sub>2</sub>A leads to shift of the Ca 2p<sub>1/2</sub> and Ca 2p<sub>3/2</sub> peaks towards the low binding energy side by 0.18 eV and 0.30 eV, respectively. This indicates that PASP-ED<sub>2</sub>A can more strongly influence the chemical environment of Ca<sup>2+</sup> in CaCO<sub>3</sub> scale than PASP, which could be because PASP-ED<sub>2</sub>A is easier to dwell on the surface of CaCO<sub>3</sub> *via* coordination adsorption.

Fig. 11 shows the Ca 2p-XPS spectra of CaSO<sub>4</sub> scales obtained with and without the addition of the scale inhibitors. The CaSO<sub>4</sub> scale obtained without the addition of the scale inhibitors shows Ca 2p<sub>1/2</sub> and Ca 2p<sub>3/2</sub> peaks at 351.16 eV and 347.62 eV, respectively. After the addition of PASP and PASP-ED<sub>2</sub>A, the Ca

2p peaks shift towards high binding energy side by 0.32 eV and 0.44 eV, respectively. Here PASP and PASP-ED<sub>2</sub>A still can cause changes in the chemical environment of Ca<sup>2+</sup> in CaSO<sub>4</sub> scale, and PASP-ED<sub>2</sub>A is superior to PASP in this sense.

### 3.4 Monitoring crystallization process of CaCO<sub>3</sub> and CaSO<sub>4</sub> scales

Fig. 12 shows the pH-time curves of the CaCO<sub>3</sub> solutions without and with the scale inhibitors (4 mg L<sup>-1</sup>). The pH values of the blank CaCO<sub>3</sub> solution and the solution with PASP decrease rapidly in the early stage of inhibition tests and stabilize around a test duration of 5 min (blank CaCO<sub>3</sub> solution) or 10 min (CaCO<sub>3</sub> solutions with PASP). After the addition of PASP-ED<sub>2</sub>A, the pH value varies at significantly slowed-down pace and reaches stabilization at greatly extended test duration. Table 1 shows the *t*<sub>ind</sub> of CaCO<sub>3</sub> in the presence of different scale inhibitors. In 0.015 mol L<sup>-1</sup> CaCO<sub>3</sub> solution, PASP-ED<sub>2</sub>A can increase the *t*<sub>ind</sub> to 131.75 min, which indicates that PASP-ED<sub>2</sub>A is superior to PASP in inhibiting the generation of CaCO<sub>3</sub> scale. Besides, the CaCO<sub>3</sub> crystals formed in the blank CaCO<sub>3</sub> solution and the CaCO<sub>3</sub> solutions with PASP or PASP-ED<sub>2</sub>A exhibit surface energies of 44.3 mJ m<sup>-2</sup>, 46.2 mJ m<sup>-2</sup> and 60.4 mJ m<sup>-2</sup>, respectively (Fig. 12(d)). This demonstrates that the addition of PASP-ED<sub>2</sub>A can significantly increase the surface energy of CaCO<sub>3</sub> crystal and reduce the nucleation rate of CaCO<sub>3</sub> scale, thereby exerting greatly improved scale inhibition performance.

Fig. 13 shows the conductivity-time curves of CaSO<sub>4</sub> solutions with and without scale inhibitors (0.75 mg L<sup>-1</sup> PASP or

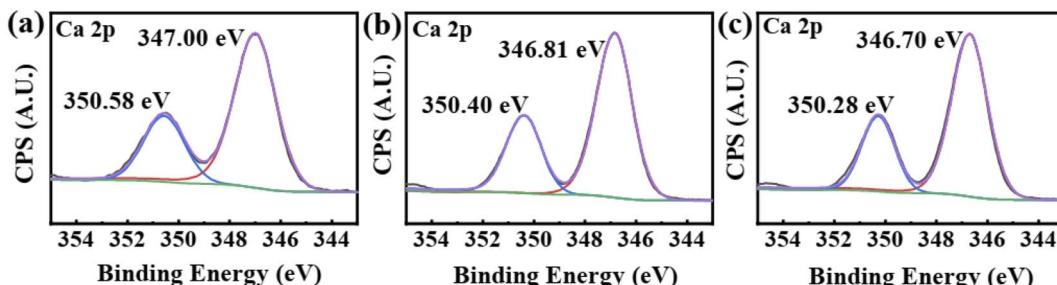


Fig. 10 XPS spectra of Ca 2p in CaCO<sub>3</sub> with different scale inhibitor. (a) Without antiscalant (b) with 30 mg L<sup>-1</sup> PASP (c) with 30 mg L<sup>-1</sup> PASP-ED<sub>2</sub>A.

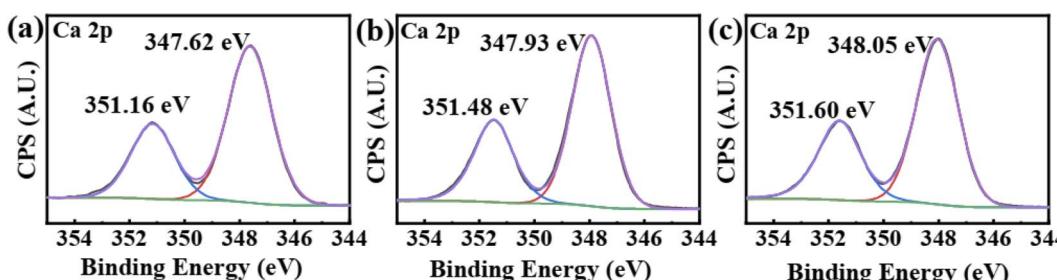


Fig. 11 XPS spectra of Ca 2p in CaSO<sub>4</sub> with different scale inhibitor. (a) Without antiscalant (b) with 4 mg L<sup>-1</sup> PASP (c) with 4 mg L<sup>-1</sup> PASP-ED<sub>2</sub>A.



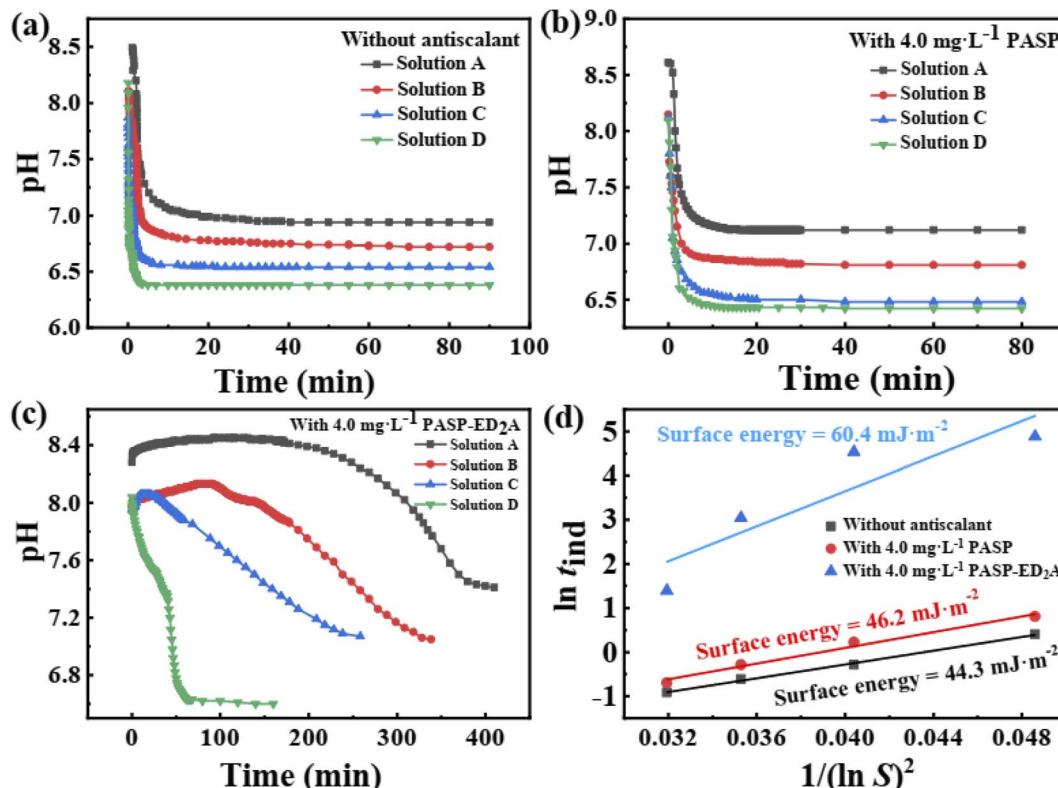


Fig. 12 pH–time curves of (a) blank  $\text{CaCO}_3$  solution and the solutions with (b)  $4.0 \text{ mg L}^{-1}$  PASP and (c)  $4.0 \text{ mg L}^{-1}$  PASP–ED<sub>2</sub>A as well as (d) relation between  $\ln t_{\text{ind}}$  and  $1/(\ln S)^2$  with or without the scale inhibitors.

PASP–ED<sub>2</sub>A). The conductivity–time curve can determine the  $t_{\text{ind}}$  of  $\text{CaSO}_4$  scale and the  $t_{\text{ind}}$  value can reflect the scale inhibition performance of the scale inhibitors. The larger the  $t_{\text{ind}}$  is, the lower the nucleation rate of  $\text{CaSO}_4$  crystal would be, and the longer the time of crystal nucleus formation and growth would be. When the concentration of blank  $\text{CaSO}_4$  solution and those  $\text{CaSO}_4$  solutions with different scale inhibitors gradually increases from  $0.07 \text{ mol L}^{-1}$  to  $0.10 \text{ mol L}^{-1}$ , their conductivity tends to increase at different paces and level off at different test durations, while their  $t_{\text{ind}}$  tends to decrease therewith at different paces (Fig. 13 and Table 2). Particularly, the  $\text{CaSO}_4$  solutions with PASP–ED<sub>2</sub>A exhibit much larger  $t_{\text{ind}}$  than the blank  $\text{CaSO}_4$  solution and the  $\text{CaSO}_4$  solutions with PASP. This corresponds to the better scale inhibition performance of PASP–ED<sub>2</sub>A in comparison to that of PASP.

Table 1 Induction time of pH test of  $\text{CaCO}_3$  solutions with and without scale inhibitors

Category	Antiscalant	CaCO <sub>3</sub> solutions with different concentration (mol L <sup>-1</sup> )			
		0.015	0.020	0.025	0.030
$t_{\text{ind}}$ (min)	Blank	1.50	0.75	0.54	0.40
	PASP	2.25	1.25	0.75	0.50
	PASP–ED <sub>2</sub> A	131.75	92.50	21.00	4.00

Table 2 Induction time of  $\text{CaSO}_4$  solutions upon conductivity tests with and without scale inhibitors

Category	Antiscalant	CaSO <sub>4</sub> solutions with different concentration (mol L <sup>-1</sup> )			
		0.07	0.08	0.09	0.10
$t_{\text{ind}}$ (min)	Blank	5.0	2.8	1.5	1.0
	PASP	12.5	4.8	3.0	2.0
	PASP–ED <sub>2</sub> A	31.0	12.5	3.3	2.3

Table 2 shows the  $t_{\text{ind}}$  of  $\text{CaSO}_4$  in the presence of different scale inhibitors. In  $0.07 \text{ mol L}^{-1}$   $\text{CaSO}_4$  solution, PASP can increase the induction time from 5.0 min to 12.5 min, while PASP–ED<sub>2</sub>A can increase the induction time to 31.0 min. This indicates that compared with PASP, the PASP–ED<sub>2</sub>A derivative can more efficiently inhibit the growth of  $\text{CaSO}_4$  scale. As can be seen from Fig. 13(d), the  $\text{CaSO}_4$  crystals formed in the blank  $\text{CaSO}_4$  solution and the  $\text{CaSO}_4$  solutions with  $0.75 \text{ mg L}^{-1}$  PASP or  $0.75 \text{ mg L}^{-1}$  PASP–ED<sub>2</sub>A exhibit surface energies of 14.8 eV, 15.4 eV and 17.7 eV, respectively. The increase in the surface energy of  $\text{CaSO}_4$  crystal upon the addition of PASP–ED<sub>2</sub>A demonstrates that PASP–ED<sub>2</sub>A can well retard the formation and growth of  $\text{CaSO}_4$  crystal nuclei, thereby exerting improved scale inhibition performance.

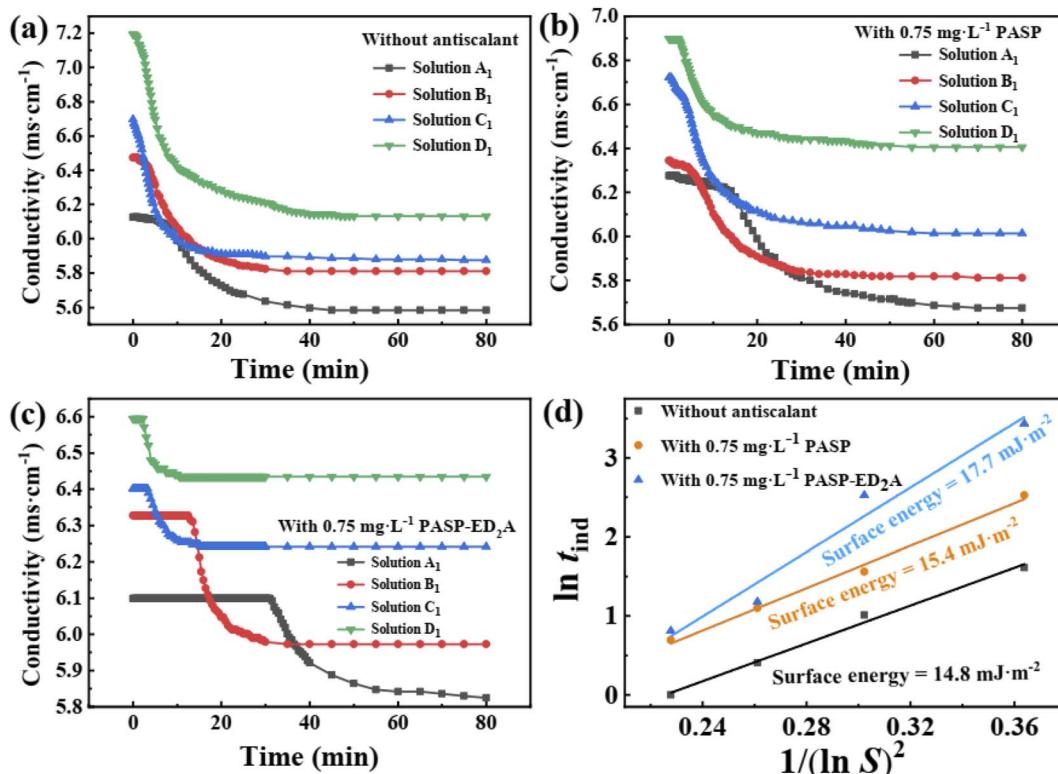


Fig. 13 Conductivity–time curves of  $\text{CaSO}_4$  crystals formed without antiscalant (a), with  $0.75 \text{ mg L}^{-1}$  PASP (b), and with  $0.75 \text{ mg L}^{-1}$  PASP–ED<sub>2</sub>A (c), as well as relation between  $\ln t_{\text{ind}}$  and  $1/(\ln S)^2$  with and without scale inhibitors (d).

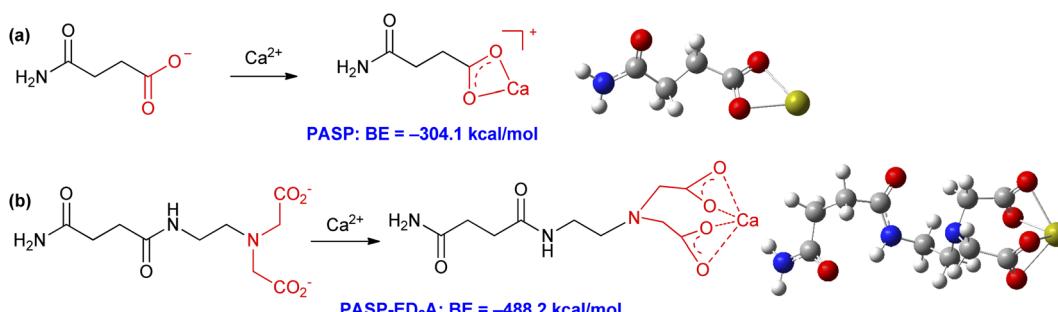


Fig. 14 Binding energies for chelation.

### 3.5 Theoretical calculation results of PASP and PASP-ED<sub>2</sub>A

From the above discussion, it can be seen that PASP and PASP-ED<sub>2</sub>A can exert their scale inhibition effect by chelating with  $\text{Ca}^{2+}$ . To better understand the coordination details, we further investigate their chelating ability with  $\text{Ca}^{2+}$  by DFT calculations (for details, please see ESI†). Fig. 14 shows the binding energies (BE) for PASP and PASP-ED<sub>2</sub>A to chelate with  $\text{Ca}^{2+}$ . The carboxyl groups in the side chains of PASP and PASP-ED<sub>2</sub>A can chelate with  $\text{Ca}^{2+}$  to form one or two four-membered rings, respectively; and the binding energies for PASP– $\text{Ca}^{2+}$  chelation and PASP-ED<sub>2</sub>A– $\text{Ca}^{2+}$  chelation are  $-304.1 \text{ kcal mol}^{-1}$  and  $-488.2 \text{ kcal mol}^{-1}$ , respectively. This means that, as compared with PASP, the PASP-ED<sub>2</sub>A

derivative is easier to combine with  $\text{Ca}^{2+}$ , thereby exerting better scale inhibition performance.

## 4. Conclusions

In summary, a novel phosphorus-free PASP derivative with side chains bearing semi-EDTA structure is rationally designed and successfully prepared. Static scale inhibition tests demonstrate that the as-prepared PASP-ED<sub>2</sub>A derivative exhibits good scale inhibition performance against  $\text{CaCO}_3$  and  $\text{CaSO}_4$  at a low concentration or a high temperature; and it exhibits better scale inhibition performance than PASP. SEM and XRD characterizations demonstrate that the addition of PASP-ED<sub>2</sub>A can affect



the morphology of  $\text{CaCO}_3$  and  $\text{CaSO}_4$  as well as the crystal shape of  $\text{CaCO}_3$ . Namely, PASP-ED<sub>2</sub>A can promote the formation of vaterite crystal and delay the formation of calcite crystal. This is because the coordination atoms in the molecular structure of PASP-ED<sub>2</sub>A can chelate with  $\text{Ca}^{2+}$ , thereby inhibiting the combination of  $\text{Ca}^{2+}$  with anions and preventing the generation of  $\text{CaCO}_3$  scale or  $\text{CaSO}_4$  scale. XPS analyses indicate that PASP and PASP-ED<sub>2</sub>A can change the chemical environment of  $\text{Ca}^{2+}$  to different extents, which could partly account for the difference in their scale inhibition performance. Besides, monitoring crystallization processes of  $\text{CaCO}_3$  and  $\text{CaSO}_4$  crystals in association with DFT calculations reveals that the  $\text{CaCO}_3$  and  $\text{CaSO}_4$  crystals generated in the presence of PASP-ED<sub>2</sub>A exhibit significantly increased surface energy, while PASP-ED<sub>2</sub>A is easier than PASP to chelate with  $\text{Ca}^{2+}$ . In other words, the PASP-ED<sub>2</sub>A derivative can more efficiently retard the formation and growth of  $\text{CaCO}_3$  and  $\text{CaSO}_4$  crystal nuclei, thereby exerting better inhibition performance against  $\text{CaCO}_3$  and  $\text{CaSO}_4$  scales than PASP. Further studies towards the development of other novel PASP derivatives are ongoing in our laboratories.

## Conflicts of interest

There are no conflicts to declare.

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