Enhancing the corrosion resistance of reinforcing steel under aggressive operational conditions using behentrimonium chloride

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Aggressive operational conditions e.g. saline media and acidic gases, e.g., CO₂ can increase the corrosion rate of reinforcing steel. Accordingly, the necessity to protect the steel under the above conditions without affecting the mechanical properties of the concrete is growing. Herein, the inhibition efficiency of a new corrosion inhibitor, behentrimonium chloride (BTC, C₂₅H₅₄ClN), is explored in a simulated-concrete pore solution (SCP) with 3.5 wt.% NaCl at different pH using electrochemical impedance spectroscopy (EIS) and polarization methods. Using only a 50 μmol L⁻¹ of BTC, we are able to measure an inhibition efficiency of 91, 79, and 71% in SCP solution with 3.5% NaCl at pH of 12.5, 10 and 7, respectively without showing any effect on the mechanical properties on the cured mortars. Temkin isotherm is used to describe the physisorption of BTC inhibitor on the steel surface. Also, the adsorption and influence of the inhibitor on the metal surface are characterized using the scanning electron microscopy, atomic force microscopy, and X-ray photoelectron spectroscopy. In conclusion, this new inhibitor shows high corrosion inhibition efficiencies under different aggressive conditions and can be used in concrete to reduce the corrosion rate of reinforcing steel without decreasing the mechanical properties of the concrete.
In this work, the effectiveness of a new inhibitor (behentrimonium chloride, C25H54ClN) for the corrosion of reinforcing steel in highly saline SPCs at ambient temperature and different pH values is explored. Behentrimonium chloride (BTC) is commonly used in hundreds of personal care products as conditioning and anti-static agents. Interestingly, Cameron et al.27, found that BTC is biologically safe for humans when used in a concentration range up to 5%. However, the European Union recently restricted its use for more than ≥1%. Consequently, we, for the first time, report the use of BTC as a corrosion inhibitor for reinforcing steel in saline SPC solutions of different pH values at significantly low concentrations of 2.5, 5, 10, and 20 ppm using electrochemical and surface analysis techniques.

Experimental

The reinforcing steel samples were abraded by silicon carbide grit papers using a grinding machine (Jean Wirts TG 200, Germany), sonicated with acetone, rinsed by deionized water and after that desiccate in air. The mild steel rebar contains (wt.%) C = 0.128, Si = 0.25, Mn = 0.7, Cu = 0.15, P = 0.04, S = 0.03, and rest was Fe. Saturated calcium hydroxide (Ca(OH)2), were used as an electrolyte to mimic SCP in 3.5 wt.% NaCl. NaCl was purchased from Sigma Aldrich and Ca(OH)2 from Riedel-de Haën. The pH of the SCP solution under investigation was 12.5 for the saturated Ca(OH)2, 10 or 7. The pH was reduced by addition of NaHCO3 powder to the SCP. The BTC inhibitor was obtained from Shanghai Dejun Chemical Technology Co., Ltd, Shanghai China, and its chemical formula is displayed in Fig. 1. Each electrochemical measurement was repeated three times to confirm the reproducibility, and the average values were reported.

Mechanical characterization.

The effect of BTC inhibitor on the compressive and flexural strength of the mortars prepared according to the ASTM C109/C109M and ASTM C348, respectively, was evaluated after different exposure times in the existence and absence of the BTC corrosion inhibitor26,29. The compressive experiments were performed using a 300 KN Tecnotest 3 compression testing machine (Tecnotest, Modena, Italy). The flexural strength experiments were utilized by a Lloyd LR 50 K universal testing machine (Ametec Inc. USA). The results are obtained by averaging three repeated tests. The mortar with 50 μmol L−1 of BTC was prepared by the mechanical mixing, in a stainless steel mixer, one part mass of cement and one and a half part mass of standard sand, with a water/cement ratio of 0.485. Then, the mold was filled with the mixture under vibration to release air bubbles, and thereafter stored in a moist atmosphere for 2 days. After that, the demolding of the prepared specimens was conducted, and the samples were kept under tap water over the test period. The cured mortar samples were removed from the water and located in a drying oven at 60 °C for 24 h before the strength test in order to shun the impact of the hydration of the concrete and to increase the strength of the measured samples.
Results and Discussion

EIS. Figures 2 and 3 display the Bode and Nyquist plots, respectively, for the reinforcing steel in SCP solutions containing 3.5 wt.%NaCl and BTC inhibitor concentrations of 12, 24, 37, 50 μmol L⁻¹ at pH values of 12.5, 10 and 7 within a frequency range from 0.01 Hz to 100 k Hz at an Ac amplitude of 5 mV. Figure 4 exhibits the equivalent circuit (EC) utilized to fit the measured EIS data to obtain the different parameters that explain the metal/solution interface. The parameters are listed in Table 1 in which $R_s$ and $R_{ct}$, are credited to the electrolyte resistance and the charge transfer resistance, respectively. However, the constant phase element is expressed by (CPE), which is used for a non-ideal double layer. The imperfectness behavior of the double layer is accredited to the following parameters (i) a non-uniform surface coverage, (ii) surface roughness, and (iii) nonuniform current distribution or corrosion rate.

The admittance and impedance of the CPE is given by:

$$1/Z_{\text{CPE}} = Y_p(j\omega)^n$$  \hspace{1cm} (1)

where $Z_{\text{CPE}}$ is the CPE impedance (Ω cm⁻²); $Y_p$ is the numerical value of the admittance $1/|Z|$, at $\omega = 1$ (rad s⁻¹) and $j^2 = -1$. $\omega$ is the angular frequency and $n$ is the deviation element which varies from 0 and 1. When $n = 1$ or 0, $Z_{\text{CPE}}$ is corresponding to an ideal capacitor or resistor, respectively.

The influence of the thickness and dielectric constant of the double layer is defined by the Helmholtz regime, given by the following formula:

$$C_{dl} = \frac{\varepsilon_0 A}{\delta}$$ \hspace{1cm} (2)

where $\varepsilon_0$ and $\varepsilon$ are the dielectric constant of air and electrolyte (mainly water), respectively and $A$ is the surface area of the working electrode.

The inhibition efficiency (IE%), is calculated using Eq. 3,

$$IE\% = \left(\frac{R_{ct1} - R_{ct2}}{R_{ct1}}\right) \times 100$$ \hspace{1cm} (3)

Table 1 exhibits that the higher the corrosion inhibitor concentration is, the higher the $R_{ct}$ and lower $C_{dl}$ values are which indicates that the ability of Cl⁻ ions to attack the reinforcing steel surface declines due to the presence of a protective adsorbed layer of BTC inhibitor. It is worth to mention that lowering the pH lead to alleviating the IE% from 91% at pH=12.5 to 79% and 72% at pH 10 and 7, respectively. Three reasons can justify the chloride-induced loss of passivity of the reinforcing steel. First, an induced de-passivation owing to adsorption of Cl⁻ ion on the passive film at potential values higher than a critical value. Second, the penetration of Cl⁻ ions into the oxide layer leading to the formation of chloride-contaminated oxides. Finally, a mechanical film breakdown
due to Cl$^-$ ions adsorption which can attenuate the surface tension, thus leading to a localized disturbance in the mechanical stability of the passive layer$^{36}$. The polarization curves for the reinforced steel in SCP solutions containing 3.5 wt.%NaCl and BTC inhibitor concentrations of 12, 24, 37, 50 μmol L$^{-1}$ at pH values of 12.5, 10 and 7 are shown in Fig. 5. The electrochemical corrosion factors such as the corrosion free potential ($E_{\text{corr}}$), pitting potential ($E_{\text{pit}}$), corrosion current density ($i_{\text{corr}}$), the polarization resistance ($R_p$), cathodic and anodic Tafel slopes ($b_c$ and $b_a$, respectively), the corrosion inhibition efficiency (IE%) and the surface coverage area ($\theta$), are calculated from Fig. 5, and recorded in Table 2. Additionally, the passive potential window is calculated using the following formula:

**Figure 3.** (a) Nyquist plots for reinforcing steel in SCP solution with 3.5 wt.%NaCl at ambient temperature using variable concentrations of BTC (12, 24, 37, 50 μmol L$^{-1}$), at variable pH values of (a) 12.5, (b) 10 and (c) 7.

**Figure 4.** Equivalent circuit utilized to fit the EIS data for reinforcing steel in SCP containing 3.5 wt.% NaCl at variable pH.
The corrosion inhibition efficiency (\(\text{IE}\%\)) is calculated using the following formula\(^3^7\),

\[
\text{Inhibition efficiency (IE\%)} = \frac{R_{\text{ct, blank}} - R_{\text{ct, inhibitor}}}{R_{\text{ct, blank}}} \times 100
\]

where \(R_{\text{ct, blank}}\) is the corrosion resistance of the steel without inhibitor, and \(R_{\text{ct, inhibitor}}\) is the corrosion resistance of the steel with inhibitor.

**Table 1.** Electrochemical elements attained from the EIS spectra of the reinforcing steel in SCP solution with 3.5 wt.% NaCl in the existence of 12, 24, 37, 50 \(\mu\)mol L\(^{-1}\) of BTC corrosion inhibitor at variable pH values.

| pH   | Inhibitor concentration (\(\mu\)mol L\(^{-1}\)) | \(R_{\text{ct}}\) \(\Omega\) cm\(^2\) | \(Y \times 10^{-5}\) s\(^2\) ohm\(^{-1}\) cm\(^{-2}\) | \(n\) | \(C_d \times 10^{-6}\) F cm\(^{-2}\) | Inhibition efficiency (IE\%) | Surface coverage (\(\Theta\)) | Goodness of fit \((\chi^2)\) |
|------|-----------------------------------------------|----------------------------------------|-----------------------------------------------|------|----------------------------------------|-----------------------------|-----------------------------|-----------------------------|
| 7    | Blank                                         | 377 ± 5.3                              | 96 ± 22                                       | 0.88 ± 0.02 | 6.1                                     | —                           | —                           | 2.1 \(\times 10^{-5}\) |
|      | 12                                            | 461 ± 42                               | 78 ± 10                                       | 0.84 ± 0.11 | 4.1                                     | 18                          | 0.18                        | 1.5 \(\times 10^{-5}\) |
|      | 24                                            | 637 ± 52                               | 70 ± 12                                       | 0.81 ± 0.08 | 3.4                                     | 41                          | 0.41                        | 3.4 \(\times 10^{-5}\) |
|      | 37                                            | 924 ± 28                               | 66 ± 6                                        | 0.78 ± 0.12 | 3.1                                     | 59                          | 0.59                        | 5.2 \(\times 10^{-5}\) |
|      | 50                                            | 1362 ± 100                             | 59 ± 8                                        | 0.75 ± 0.21 | 2.5                                     | 72                          | 0.72                        | 1.8 \(\times 10^{-5}\) |
| 10   | Blank                                         | 643 ± 18                               | 89 ± 11                                       | 0.85 ± 0.02 | 5.3                                     | —                           | —                           | 6.5 \(\times 10^{-6}\) |
|      | 12                                            | 863 ± 24                               | 74 ± 15                                       | 0.81 ± 0.09 | 3.8                                     | 25                          | 0.25                        | 4.2 \(\times 10^{-6}\) |
|      | 24                                            | 1349 ± 31                              | 61 ± 17                                       | 0.80 ± 0.03 | 3.2                                     | 52                          | 0.52                        | 1.1 \(\times 10^{-4}\) |
|      | 37                                            | 1953 ± 52                              | 50 ± 13                                       | 0.79 ± 0.05 | 2.7                                     | 67                          | 0.67                        | 2.4 \(\times 10^{-6}\) |
|      | 50                                            | 3105 ± 120                             | 44 ± 28                                       | 0.72 ± 0.12 | 2.1                                     | 79                          | 0.79                        | 1.1 \(\times 10^{-5}\) |
| 12.5 | Blank                                         | 960 ± 66                               | 80 ± 32                                       | 0.82 ± 0.06 | 4.5                                     | —                           | —                           | 8.1 \(\times 10^{-5}\) |
|      | 12                                            | 2678 ± 133                             | 64 ± 9                                        | 0.75 ± 0.13 | 3.5                                     | 64                          | 0.64                        | 7.7 \(\times 10^{-6}\) |
|      | 24                                            | 5009 ± 149                             | 49 ± 15                                       | 0.72 ± 0.09 | 2.8                                     | 80                          | 0.80                        | 3.6 \(\times 10^{-5}\) |
|      | 37                                            | 7680 ± 352                             | 39 ± 10                                       | 0.66 ± 0.17 | 2.1                                     | 87                          | 0.87                        | 8.1 \(\times 10^{-6}\) |
|      | 50                                            | 10526 ± 420                            | 28 ± 15                                       | 0.56 ± 0.27 | 1.1                                     | 91                          | 0.91                        | 1.9 \(\times 10^{-5}\) |

\(E_{\text{pit}} - E_{\text{corr}}\)  

The corrosion inhibition efficiency (\(\text{IE}\%\)), is calculated using the following formula\(^3^7\),

\[
E_{\text{pit}} - E_{\text{corr}} = \frac{E_{\text{pit}} - E_{\text{corr}}}{E_{\text{pit}} - E_{\text{corr}}} \times 100
\]
where $i_1$ and $i_2$ are the corrosion current densities of reinforcing steel in the absence and existence of the BTC corrosion inhibitor, respectively.

The surface coverage area ($\theta$) is calculated utilizing Eq. 6,

$$\theta = \frac{IE\%}{100}$$

and the polarization resistance ($R_p$), was detected using the Stern–Geary equation.

$$R_p = \frac{i_2}{b_a (b_a + b_c)}$$

The polarization curves show the breakdown of the passive film before and after the addition of BTC inhibitor at pH 12.5, see Table 2. However, increasing the inhibitor concentration shifts the pitting potentials ($E_{pit}$), towards the more noble values indicating that the passive layer formed more stabilized by the presence of BTC inhibitor. Moreover, the passive potential window at pH 12.5 is 0.18, which increased to 0.25, 0.27, 0.32 and 0.38 by the addition of 12, 24, 37, 50 $\mu$mol L$^{-1}$ of the BTC inhibitor, respectively. The attack of chloride species to the reinforcing steel surface in SCP can lead to loss of its passive layer if the concentration of the chloride species is adequately high. For reinforcing steel in concrete, the degree to which Cl$^-$ ions can damage the passive layer is related to the alkalinity of the environment. In chloride-free alkaline conditions, the passive layer on the mild steel breaks

**Table 2.** The electrochemical factor derived from polarization plots of the reinforcing steel in SCP solutions including 3.5 wt.% NaCl and BTC inhibitor concentrations of 12, 24, 37, 50 $\mu$mol L$^{-1}$ at pH values of 12.5, 10 and 7.

| pH values | Inhibitor concentration ($\mu$mol L$^{-1}$) | $i_{corr}$ (µA cm$^{-2}$) | $i_p$ (µA cm$^{-2}$) | $E_{corr}$ (mV SCE) | $E_{p}$ (mV SCE) | $E_{p}-E_{corr}$ (mV SCE) | $R_c$ (V decade$^{-1}$) | $R_s$ (V decade$^{-1}$) | $R_p$ (Ω cm$^2$) | IE% | surface coverage ($\theta$) |
|-----------|--------------------------------------|--------------------------|--------------------------|---------------------|---------------------|------------------------|---------------------|---------------------|-------------------|-----|-------------------------|
| 12.5      | Blank                                | 13                       | 2.0 × 10$^{-4}$         | −0.41               | −0.601              | 0.187                  | 0.11                | 0.076               | 1502              | —   | —                       |
|           | 12                                   | 5.2                      | 6.7 × 10$^{-5}$         | −0.34               | −0.598              | 0.254                  | 0.081               | 0.061               | 2888              | 56  | 0.56                    |
|           | 24                                   | 3.2                      | 5.0 × 10$^{-5}$         | −0.33               | −0.601              | 0.271                  | 0.077               | 0.059               | 4590              | 76  | 0.76                    |
|           | 37                                   | 2.5                      | 4.2 × 10$^{-5}$         | −0.28               | −0.602              | 0.322                  | 0.072               | 0.056               | 5471              | 81  | 0.81                    |
|           | 50                                   | 1.6                      | 3.9 × 10$^{-5}$         | −0.21               | −0.594              | 0.384                  | 0.068               | 0.048               | 7636              | 88  | 0.88                    |
| 10        | Blank                                | 20                       | —                       | —                   | −0.71                | —                     | 0.091               | 0.091               | 988               | —   | —                       |
|           | 12                                   | 15                       | —                       | —                   | −0.639               | —                     | 0.087               | 0.081               | 1214              | 22  | 0.22                    |
|           | 24                                   | 10                       | —                       | —                   | −0.665               | —                     | 0.075               | 0.079               | 1671              | 52  | 0.52                    |
|           | 37                                   | 8                        | 1.23 × 10$^{-5}$        | —                   | −0.635               | 0.058                 | 0.061               | 0.066               | 1721              | 63  | 0.63                    |
|           | 50                                   | 5                        | 9.7 × 10$^{-5}$         | —                   | −0.585               | 0.376                 | 0.058               | 0.058               | 2518              | 78  | 0.78                    |
| 7         | Blank                                | 33                       | —                       | —                   | —                   | —                     | 0.098               | 0.120               | 709               | —   | —                       |
|           | 12                                   | 28                       | —                       | —                   | —                   | —                     | 0.087               | 0.110               | 755               | 15  | 0.15                    |
|           | 24                                   | 21                       | —                       | —                   | —                   | —                     | 0.080               | 0.109               | 958               | 36  | 0.36                    |
|           | 37                                   | 14                       | —                       | —                   | —                   | —                     | 0.071               | 0.111               | 1344              | 57  | 0.57                    |
|           | 50                                   | 9.5                      | —                       | —                   | —                   | —                     | 0.116               | 0.091               | 2332              | 71  | 0.71                    |

**Figure 6.** Temkin adsorption plots for reinforcing steel in SCP solution containing 3.5 wt.% NaCl in the existence of 12, 24, 37, 50 $\mu$mol L$^{-1}$ of BTC corrosion inhibitor at variable pH values of 12.5, 10, and 7.
Table 3. The calculated thermodynamic parameters derived from Temkin plot.

| pH values | Slope | α  | Intercept | $K_{ads} \times 10^4$ (L mole$^{-1}$) | $\Delta G_{ads}^\circ$ (kJ mol$^{-1}$) |
|-----------|-------|----|-----------|-------------------------------------|-------------------------------------|
| 12.5      | −0.33 | 0.17 | −3        | 0.88                                | −32                                 |
| 10        | −0.36 | 0.14 | −3.5      | 1.6                                 | −33                                 |
| 7         | −0.39 | 0.13 | −3.9      | 2.2                                 | −34                                 |

Figure 7. SEM images for the reinforcing steel (a,c,e) before and (b,d,f) after immersion in SCP solution containing 3.5 wt.% NaCl in existence of 50 μmol L$^{-1}$ of BTC corrosion inhibitor at variable pH values of (a,b) 12.5, (c,d) 10, and (e,f) 7 for 24 h.
The highest attained IE% was 88% at 50 μmol L⁻¹ of the BTC inhibitor at pH = 12.5. It can be seen that the values of ba and bc diminished upon the addition of the inhibitor indicating that BTC is a mixed type inhibitor. It is noteworthy to mention that the tabulated values of the corrosion density (i_corr), shifts towards decreases with increasing the concentration of the BTC inhibitor. However, these values are not in accordance with reported articles in references12,39. In fact, the diffusion of chloride species (Cl⁻), in cementitious materials immersed in saline water is a difficult process, which includes numerous chemical and physical interactions. Cl⁻ ions can bound chemically or physically through the cement paste, thus reducing the segment of free

Figure 8. AFM images for the reinforcing steel surface (a,c,e) before and (b,d,f) after immersing the reinforcing steel for 24 h in SCP solution containing 3.5 wt.% NaCl in existence of 50 μmol L⁻¹ of BTC corrosion inhibitor at variable pH values of (a,b) 12.5, (c,d) 10, and (e,f) 7.

| pH   | Rₐ in absence of BTC (nm) | Rₐ in presence of BTC (nm) |
|------|--------------------------|---------------------------|
| 12.5 | 27                       | 15                        |
| 10   | 47                       | 23                        |
| 7    | 70                       | 36                        |

Table 4. The surface roughness values (Rₐ), of the reinforcing steel before and after addition of BTC inhibitor in saline water for 24 h at variable pH values.

down at a potential of +560 mV SCE38. The highest attained IE% was 88% at 50 μmol L⁻¹ of the BTC inhibitor at pH = 12.5. It can be seen that the values of ba and bc diminished upon the addition of the inhibitor indicating that BTC is a mixed type inhibitor. It is noteworthy to mention that the tabulated values of the corrosion density (i_corr), shifts towards decreases with increasing the concentration of the BTC inhibitor. However, these values are not in accordance with reported articles in references12,39. In fact, the diffusion of chloride species (Cl⁻), in cementitious materials immersed in saline water is a difficult process, which includes numerous chemical and physical interactions. Cl⁻ ions can bound chemically or physically through the cement paste, thus reducing the segment of free
Cl⁻ species that can diffuse easily in the concrete pore solutions. Furthermore, the internal electric field generated from the anions and cations will accelerate the ions that possess low diffusion coefficients and decelerate the ions that have high diffusion coefficients in order to keep the electro-neutrality status.

Adsorption isotherm. In order to understand and estimate the adsorption route of BTC on steel surface, different adsorption isotherms are checked using the measured data from the poanlarization plots e.g. Langmuir, Frumkin and Temkin isotherms using the following equations:

**Langmuir**

\[
\frac{C_{inh}}{\theta} = \frac{1}{K_{ads}} + C_{inh}
\]

**Frumkin**

\[
\log[C \times \left( \frac{\theta}{1 - \theta} \right)] = 2.303 \log K + 2\alpha \theta
\]

**Temkin**

\[
\exp(-2\alpha \theta) = K_{ads} C
\]

where \(\theta\) is the surface coverage of the reinforcement steel, \(C\) is the concentration of the BTC inhibitor species, \(\alpha\) is the adsorbate interaction factor and \(K_{ads}\) is the adsorption–desorption equilibrium constant. The fitting outcomes showed that BTC inhibitor obeys Temkin isotherm, see Fig. 6.

After reorganizing Eq. (10), the following expression is attained:

\[
\theta = \frac{1}{-2\alpha} \ln C + \frac{1}{-2\alpha} \ln K_{ads}
\]

It can be deduced from Eq. (11) that both of the slope and intercept are calculated from \(1/(-2\alpha)\) and \((1/(-2\alpha))\ ln K_{ads}\) respectively.

Knowing the \(K_{ads}\) values at various pH values, the standard Gibbs free energy change of adsorption (\(\Delta G^\circ_{ads}\)) are calculated using Eq. 12.

\[
K_{ads} = \frac{1}{55.5} e^{-\frac{\Delta G^\circ_{ads}}{RT}}
\]

Table 3 summarizes the values of the \(\alpha\), \(K_{ads}\) and \(\Delta G^\circ_{ads}\). Values of \(\Delta G^\circ_{ads} \geq -20\) kJ mol⁻¹, showing a physisorption adsorption, while \(\Delta G^\circ_{ads} \leq -40\) kJ mol⁻¹ depicts chemisorption adsorption reactions. Consequently, the intermediate values of \(\Delta G^\circ_{ads}\) shown in Table 3 \((-32, -33\) and \(-34\) kJ mol⁻¹), usually elucidate that chemi-physisorption of BTC inhibitor occurs on the reinforcing steel at different pH values of 12.5, 10 and 7, respectively. However, since there is no free electron pair existing in the molecular structure of the BTC inhibitor that can form coordinated covalent bond with the vacant d-orbitals in Fe (chemisorption), therefore it is more favorable that the adsorption mechanism is a strong physisorption rather than a chemi-physisorption one. Physical adsorption takes place rapidly because of weak bondings such as Van der Waal’s or electrostatic attractive forces between inhibitor species and metal surface, and is directly influenced by the electronegativity of the inhibitor compounds. The residence time for a physically adsorbed inhibitor is short, and its interaction with...
the steel surface is directly associated with the corrosion free potential of the metal corrosion with respect to the potential of zero charge.

Figure 7 exhibits the SEM of the reinforcing steel coupons after immersion in SCP including 3.5 wt.% NaCl at different pH values of 12.5, 10, 7 in the existence and absence of 50 μmol L⁻¹ of the BTC inhibitor for 24 h. It is clear that in case of the absence of the corrosion inhibitor, deep pits were formed and their number is suppressed as the pH of the medium increases. Nonetheless, in the existence of the corrosion inhibitor, the number and pits size are considerably reduced at the same pH values. Moreover, the pH values before and after immersion are measured. It is found that the pH values in the absence of the corrosion inhibitors are lowered from 12.5, 10 and 7 to 10, 8.7 and 5.7, respectively. However, in the existence of the BTC inhibitor the pH values slightly dropped from 12.5, 10 and 7 to 11.5, 9.3 and 6.3, respectively.

Surface topography and surface roughness of the reinforcing steel are explored after immersion in 3.5 wt.% NaCl of variable pH values for 24 h in the existence and absence of 50 μmol L⁻¹ of the BTC inhibitor using AFM, as depicted in Fig. 8. It is noted that the surface roughness (Rₐ), escalates as the pH alleviates in the absence

Figure 10. High resolution XPS spectrum of (a) Cl 2p, (b) C 1s, (c) Ca 2p, (d) N 1s (e) O 1s and (f) Fe 2p after immersing the reinforcing steel for 24 h in SCP solution containing 3.5 wt.% NaCl in existence of 50 μmol L⁻¹ of BTC corrosion inhibitor at pH Σ12.5.
∆ BTC inhibitor is physisorbed on the reinforcing steel surface, which is matching with the effective if carbonation of the concrete happens and the pH of the concrete is lowered. Based on the adsorption badly affect its mechanical features50. Therefore, the mechanical characteristics of cured mortars are investigated

Table 5. Flexural and compressive strength results of the as-prepared cured mortars after different curing times.

| Exposure time (days) | Flexural strength (MPa) | Compression strength (N mm⁻²) |
|---------------------|-------------------------|-------------------------------|
|                     | Blank | BTC | Blank | BTC |
| 7                   | 5.9   | 5.6 | 42.2  | 39.1 |
| 14                  | 6.3   | 6.3 | 44.2  | 44.2 |
| 21                  | 6.5   | 6.2 | 47.31 | 47.1 |
| 28                  | 6.6   | 6.4 | 47.4  | 47.3 |

of the corrosion inhibitor, see Table 4. However, Rₐ is decreased significantly in the existence of the BTC inhibitor in the deleterious medium signifying the construction of an adsorbed protective layer of BTC inhibitor on the metal surfaces, which retards the attack of the Cl⁻ species.

The wide scan spectrum (Fig. 9) and the high resolution XPS spectra (Fig. 10) are obtained after immersing the reinforcing steel for 24h in SCP including 3.5 wt.% NaCl in the existence of 50 μmol L⁻¹ of BTC corrosion inhibitor at pH 12.5.

The Cl 2p spectrum is deconvoluted into two components at BE of 199.1 and 200.7 eV which are attributed to Cl⁻ and FeClₓ, respectively⁴¹, see Fig. 10a. It is noteworthy that the peak intensity of Cl⁻ species is low; indicating that the adsorbed BTC inhibitor lowers the adsorption affinity of the Cl⁻ ions to the metal surface which subsequently lessens the corrosion rate. The adsorption of the BTC inhibitor on the reinforcing steel surface is further confirmed by the analysis of C spectra, which showed the presence of CN⁻ bonds, OH⁻, and Fe(OH)₃, respectively⁴₂-⁴⁶, see Fig. 10b. However, Ca 2p spectrum shown in Fig. 10c is decomposed into two bands at 347.8 eV and 351.5 eV that are credited to Ca 2P3/2 and 2P1/2 respectively, of CaO/Ca(OH)₂. Figure 10d shows the appearance of N 1s peaks at 399.4 and 402.5 eV, characteristics of N–CH₂ and N–quaternary nitrogen, respectively⁴³-⁴⁶. This approves the adsorption of the BTC inhibitor on the reinforcing steel surface. There is no peak for C–N–Fe bonding was observed at 397.7–398.6 eV, suggesting that BTC inhibitor was adsorbed on the reinforcing steel through physisorption⁴⁷. The XPS spectrum of O 1 s in Fig. 10e, exhibits three peaks at 530.3, 531.7 and 534.2 eV, that are credited to O²⁻ of iron oxides, OH⁻ of hydrous iron oxides (FeOOH), and H₂O, respectively⁴³,⁴⁶. On the other hand, Fe 2p spectra in Fig. 10f is deconvoluted into six peaks. In fact, the interpretation of Fe 2p spectra is a complex owing to the existence of iron (Fe), in variable oxidation states of Fe°, Fe₂⁺, Fe³⁺, and satellites of Fe⁶⁺ species. The (Fe 2p₃/2), XPS spectra at high resolution involves four bands at 707.1 eV that is related to the metallic iron, 710.9 eV for Fe₂⁺ of FeO(OH) and 713.9 eV, which could be attributed to a mixture of (Fe²⁺ & Fe³⁺), in different forms of iron (II) oxide (FeO), iron (II) hydroxide Fe(OH)₂, iron (III) hydroxide Fe(OH)₃, FeOOH, iron (III) oxide (Fe₂O₃), and magnetite (Fe₃O₄)⁴⁸. The shake up phenomenon found at 716.6 and 719.8 eV is ascribed to Fe²⁺ and Fe³⁺, respectively. The spectra of the Fe 2p₁/2 peaks at BE of 722.7 and 725.3 eV can be ascribed to Fe₂O₃ and FeO(OH), respectively⁴⁹.

Mechanical properties. Although corrosion inhibitors can protect steel against corrosion, however it can badly affect its mechanical features⁵⁰. Therefore, the mechanical characteristics of cured mortars are investigated in the presence and absence of a 20 ppm (50 μmol L⁻¹) of the BTC inhibitor. This is achieved through measuring the flexural and compressive strength of cement, see Table 5. It can be observed that there is almost no change in the mechanical properties of the concrete after the addition of the inhibitor, which is attributed to the low concentration of the BTC.

Conclusions
A new BTC corrosion inhibitor for reinforcing steel is investigated in 3.5 wt.% NaCl at different pH values. Tafel plots indicated that BTC is a mixed type inhibitor. The BTC inhibitor showed a corrosion inhibition efficiency (IE%) of 88, 78 and 71% in 3.5 wt.% NaCl using 50 μmol L⁻¹ at pH values of 12.5, 10 and 7, respectively, which is effective if carbonation of the concrete happens and the pH of the concrete is lowered. Based on the adsorption isotherm calculations, BTC inhibitor showed the best fitting with Temkin isotherm. XPS results illustrate that BTC inhibitor is physisorbed on the reinforcing steel surface, which is matching with the ΔG°ads calculations. The surface roughness of the metal surface is significantly decreased upon the addition of BTC inhibitor as shown in the AFM results confirming a high corrosion inhibition efficiency of BTC. Additionally, no change in the mechanical features of concrete is observed upon the addition of BTC inhibitor, which allows using it in concrete without any reservation.

Data availability
The raw/processed data required to reproduce these findings could not be shared at this time due to time limitations. However, it will be available on request.

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Author contributions

Ahmed Bahgat Radwan, Mostafa Sliem and Noor Yusuf were responsible for the experimental work including preparation and characterization. Dr. Nasser Alnuaimi supervised the concrete preparation and mechanical testing section. Dr. Aboubakr Abdullah was responsible for the corrosion section and the overall manuscript gathering, reviewing and submission.

Competing interests

The authors declare no competing interests.

Additional information

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