Electrochemical analysis of the inhibition performance of glucobiogen on low-carbon steel in neutral chloride solution

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Abstract. The inhibition performance of glucobiogen (GBN) on low-carbon steel (LCS) corrosion in neutral chloride solution (3.5% NaCl in H₂O) was evaluated by potentiodynamic polarization, metal weight loss measurement and optical microscopy characterization. Data obtained showed GBN effectively inhibited the LCS corrosion with inhibition efficiency exceeding 80 and 90% from potentiodynamic polarization test and weight loss measurement. GBN, at lowest concentration performed poorly with inhibition efficiency value below 50%. The inhibition performance of GBN showed mixed type inhibition effect with higher tendency for anodic inhibition from relative shift in corrosion potential. Inhibitor adsorption on LCS was determined to be physisorption with respect to the Langmuir and Frumkin adsorption isotherm. The optical microscopy characterization revealed that GBN hindered the formation of corrosion pits and general surface deterioration of LCS.

1. Introduction
Metallic corrosion is a major problem in petrochemical, mining and automobile industries etc. due to the extent of damage caused and the consequential cost of repair and maintenance. Carbon steels have extensive application across nearly all industries due to their relatively low cost, ease of fabrication and desirable mechanical and physical properties [1]. However, these steels have weak corrosion resistance which negatively impacts their versatility, application and operational lifespan [2,3]. Chemical compounds known as corrosion inhibitors have been proven to be effective in minimizing carbon steel corrosion [4-9]. Corrosion inhibitor modifies and suppresses the electrochemical properties and reaction mechanisms of corrosive environments in addition to their reaction with metallic surfaces [10-13]. Research performed previously has proven that non-toxic organic compound are long-term solution to toxic chemical compounds such as chromates, nitrates etc. [14-16]. Glucobiogen obtained from gluconic acid is a white needlelike crystalline solid, partially soluble in H₂O [17]. The compound has immense benefit medically and as health mineral supplements. Application of glucobiogen in acidic solutions, low chloride solutions and cooling water systems has produced mixed results necessitating further research for optimization of its corrosion inhibiting properties [18,19]. In contribution to research on the inhibition performance of glucobiogen, this article is focuses on the electrochemical analysis of the inhibition performance of the compound on low carbon steel in neutral chloride solution.

2. Materials and methods
Low-carbon steel (LCS) with 0.7 cm diameter was cut into 5 test specimens. Each specimen was embedded in hardened resin paste, grinded with emery abrasive papers (80, 120, 240, 320, 400, 600,
800 and 1000 grits), polished with diamond polishing paste and thereafter washed with distilled H₂O and acetone for potentiodynamic polarization technique. 7g of recrystallized NaCl was added to 200 ml of distilled H₂O to simulate neutral chloride solution (artificial seawater). Glucobiogen (GCN) obtained from Sigma Aldrich. USA was formulated in volumetric concentrations of 0.75%, 1.25%, 1.75% and 2.25% per 200 ml of the neutral chloride solution. GCN is non-toxic with molecular weight of 430.373 g/mol and molecular formular of C₁₂H₂₂CaO₁₄. Potentiodynamic polarization test was done with Digi-Ivy 2300 potentiostat at 25°C ambient temperature. Resin mounted LCS electrodes (exposed surface area of 0.38 cm²), Pt counter electrode and Ag/AgCl reference electrode were immersed in neutral chloride solution, and connected to the potentiostat-computer interface. Potentiodynamic measurement was performed between potentials of -1.5 V to 0.5 V at a scan rate of 0.0015 V/s. An Omax trinocular metallurgical microscope was used to study and capture images of LCS surface before corrosion and after corrosion test with and without GCN inhibitor.

3. Results and discussion

3.1. Potentiodynamic polarization and microscopy characterization

Potentiodynamic polarization curves of LCS corrosion in neutral chloride solution at 0% to 2.25% GCN is shown in figure 1. Table 1 depicts the results gotten from the polarization test. The optical morphology of LCS before corrosion and after corrosion test in neutral chloride solution at 0% GCN compound is shown in figures 2(a) and 2(b). Figures 3(a) and 3(b) shows the optical morphology of LCS surface after corrosion at 0.75% GCN and 2.25% GCN concentration. The corrosion rate of LCS at 0% GCN is 1.56 mm/y due to the oxidation of LCS surface as shown in figure 2(b). Corrosion pits and general surface deterioration are visible due to oxidation of the substrate Fe²⁺. LCS corrosion rate in the presence of GCN differs from the control solution (0% GCN) though at 0.75% GCN concentration the corrosion rate is 0.92 mm/y with corresponding inhibition efficiency of 40.72%. LCS surface morphology at this concentration (figure 3(a)) is a mild improvement of the image at figure 2(b). GCN inhibition efficiency at 1.25% to 2.25% GCN compound was generally above 80% due to effective inhibition of the corrosion reaction processes. The protective reaction product of Fe²⁺-GCN precipitate passivates on LCS as shown in figure 3(b) and the extended passivated region of the inhibited polarization plots in figure 1. The passivated regions of the polarization curves in the presence of specific concentrations of GCN extends further than the curve without GCN, confirming anodic inhibition effect of GCN on LCS surface. The degree of wear in figure 3(b) is much lower; the lines resulting from machining are still visible while corrosion pits are absent. The maximum corrosion potential shift in table 1 between the inhibited and non-inhibited steel is 75 mV in the anodic direction, confirming the inhibitor to be mixed type with dominant anodic inhibition effect.

Table 1. Potentiodynamic polarization data for LCS corrosion inhibition in neutral chloride solution at 0% - 2.25% GCN concentration.

| Sample | GCN Conc. (%) | LCS C_r (mm/y) | GCN ðϕ | C_l (A) | C_i (A/cm²) | C_p (V) | R_p (Ω) | B_k (V/dec) | B_s (V/dec) |
|--------|---------------|----------------|----------|---------|-------------|---------|---------|-------------|-------------|
| A      | 0             | 1.56           | 0        | 1.55E-04| 1.37E-04   | -0.989  | 119.30  | -9.662      | 6.526       |
| B      | 0.75          | 0.92           | 40.72    | 9.16E-05| 8.10E-05   | -0.975  | 358.90  | -9.547      | 4.212       |
| C      | 1.25          | 0.26           | 83.06    | 2.62E-05| 2.32E-05   | -0.931  | 981.50  | -9.628      | 1.785       |
| D      | 1.75          | 0.23           | 85.14    | 2.30E-05| 2.03E-05   | -0.926  | 1119.00 | -9.785      | 1.358       |
| E      | 2.25          | 0.31           | 80.25    | 3.05E-05| 2.70E-05   | -0.921  | 813.60  | -9.463      | 2.042       |
Figure 1. Potentiodynamic polarization plots for LCS corrosion inhibition in neutral chloride solution at 0% - 2.25% GCN concentration.

Figure 2. Optical microscopic images of (a) LCS surface before corrosion test and (b) LCS surface after corrosion in artificial seawater at 0% GCN.

Figure 3. Optical microscopic images of GCN inhibited LCS surface in artificial seawater (a) at 0.75% GCN and (b) 2.25% GCN.

3.2. Weight loss measurement
Graphical curves of LCS corrosion rate against time of exposure is shown in figure 4(a) while figure 4(b) depicts the curve of GCN inhibition efficiency against exposure time. The results obtained from weight loss measurement at 216 h are shown in table 2. Corrosion rate of LCS at 0% GCN concentration is 0.0045 mm/y at 48 h due to onset of surface oxidation of LCS surface which subsequently decreased to 0.00104 mm/y at 216 h as a result of the weakened electrolyte. The corrosion rate value of LCS at 0% GCN significantly differs from the general corrosion rate value of LCS obtained at 0.75% GCN concentration. At this concentration, the corrosion rate at 48 h is 0.0008 mm/y and at 216 h, it peaked at 0.0007 mm/y. The corresponding inhibition efficiency of GCN at (0.75% GCN) is 33%. GCN
concentration at 1.25, 1.75, and 2.25% GCN decreased the corrosion rate values of LCS to 0.00009, 0.00002, and 0.00006 mm/y at 216 h, corresponding to inhibition efficiency of 90.97, 97.87, and 94.58%.

![Graph](image)

**Figure 4.** Graphical plot of (a) LCS corrosion rate versus exposure time and (b) GCN inhibition efficiency versus exposure time.

| LCS specimen | LCS weight loss (g) | GCN concentration (%) | LCS corrosion rate (mm/y) | GCN inhibition efficiency (%) |
|--------------|---------------------|------------------------|---------------------------|-------------------------------|
| A            | 0.1218              | 0                      | 0.00104                   | 0                             |
| B            | 0.0816              | 0.75                   | 0.00070                   | 33.00                         |
| C            | 0.0110              | 1.25                   | 0.00009                   | 90.97                         |
| D            | 0.0026              | 1.75                   | 0.00002                   | 97.87                         |
| E            | 0.0066              | 2.25                   | 0.00006                   | 94.58                         |

**Table 2.** Data obtained from coupon measurement at 216 h.

3.3. **Adsorption isotherm studies**

GCN interaction and adsorption on LCS surface was also studied through adsorption isotherms. Langmuir and Frumkin isotherm models produced the best fit among the isotherms studied with high correlation coefficients values. Figure 5(a) shows the Langmuir plot of $\frac{c_{GCN}}{\theta}$ vs $C_{GCN}$ with correlation coefficient of 0.9898. Figure 5(b) shows the Frumkin plots of $\log\left[\frac{\theta}{(1 - \theta)c}\right]$ versus $\theta$ with correlation coefficient of 0.9780.
3.4. Thermodynamics of inhibitor adsorption

Results for the Gibbs free energy are presented in table 3. The highest $\Delta G_{\text{ads}}$ value obtained for GCN is -27.37 KJmol$^{-1}$ while the lowest $\Delta G_{\text{ads}}$ value is -18.23 KJmol$^{-1}$. The highest and lowest $\Delta G_{\text{ads}}$ values obtained show the mechanism of GCN adsorption on LCS is through physisorption mechanism. Lateral interaction effect was shown to be insignificant due to the non-linear relationship between the $\Delta G_{\text{ads}}$ value and GCN concentration.

Table 3. Results for the Gibbs free energy ($\Delta G_{\text{ads}}$), surface coverage ($\Theta$) and equilibrium constant of adsorption ($K_{\text{ads}}$) for GCN adsorption on neutral chloride solution.

| Sample | GCN concentration (M) | Surface coverage ($\Theta$) | Equilibrium constant of adsorption ($K_{\text{ads}}$) | Gibbs free energy, $\Delta G$ (KJmol$^{-1}$) |
|--------|-----------------------|----------------------------|-----------------------------------------------|---------------------------------------------|
| 1      | 0                     | 0                          | 0                                             | 0                                           |
| 2      | 1.74E-02              | 0.330                      | 28.3                                          | -18.23                                      |
| 3      | 2.90E-02              | 0.910                      | 346.8                                         | -24.45                                      |
| 4      | 4.07E-02              | 0.979                      | 1127.5                                        | -27.37                                      |
| 5      | 5.23E-02              | 0.946                      | 333.9                                         | -24.35                                      |

4. Conclusion

Glucobiogen effectively suppressed the low-carbon steel corrosion in neutral chloride media with average inhibition efficiency above 80 and 90% from different electrochemical tests. Glucobiogen showed the mixed-type inhibition effect with dominant anodic properties. Thermodynamic calculations prove that glucobiogen was adsorbed through the physisorption mechanism, according to the Langmuir and Frumkin adsorption isotherms. Corrosion pits visible on the non-inhibited steel were absent on the inhibited steel.

Acknowledgment

The authors appreciate the financial support of this study by the Covenant University, Ogun State, Nigeria.

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