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Analysis of corrosion rate of buried API 5L× 70 steel pipeline in soil by Taguchi technique

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Abstract
Several studies have identified corrosion of buried steel pipeline to be attributed to certain factors in the soil such as: salt concentrations, type of soil, temperature, pH, moisture content, earth currents, welded joint and microorganism. In this study, Taguchi design of experiment was used to optimized three factors (pH, clay content and moisture content), having three levels each. Corrosion test was conducted to determine the corrosion rates of the samples. The results of analysis showed that S/N ratios significantly affected the corrosion rate by the levels in the Taguchi orthogonal array. It was established that clay content is the major influential parameter affecting the corrosion rate. The optimized corrosion rate parameters for the smaller-the-better criteria are clay content 1 wt%, pH 4-8, and moisture content 20-40%.

Keywords: Corrosion, pH, clay content, moisture content, steel pipeline

1. Introduction

Buried steel pipes are used for the distribution of several products ranging from petroleum, gas, municipal waste, dam structures (Balcik and Unal, 2023) [2]. Depending on the application, some steel pipes can be coated, uncoated, stainless or plain carbon steel. Because these steel pipes are buried in the soil, they are exposed to a different environment that is most likely going to subject them to corrosion. This is because factors that encourage corrosion are present in the soil ranging from moisture, dissolved chemicals, pH value, type of soil, salt concentration, hard particles, microorganism, earth currents (Alternating or direct currents) and others like improper steel pipes welds, temperature (Sjogren *et al*., 2011, Balcik and Unal, 2023) [21, 2].

Many studies on buried steel pipeline includes; Benmousa *et al*., (2006) [4] studied corrosion behavior of API 5L X-60 pipeline steel exposed to near-neutral pH soil simulating solution. It was observed that steel corrosion increases as the current density increases with temperature ranging from 20 -60 ^{0}C. Liu *et al*., (2010) [16] researched on the effect of soil compositions on the electrochemical corrosion behavior of carbon steel in simulated soil solution. The results showed that Ca^{2+} and Mg^{2+} reduces the corrosion current density while K^{+}, SO_4^{2-} increases it. Corrosion resistance of stainless-steel pipes in soil was studied by (Sjogren *et al*., 2011) [21]. The results recommended the use of stainless steels under different soil conditions. Bayesian modeling of external corrosion in underground pipelines based on the integration of Markov chain Monte Carlo techniques and clustered inspection data was investigated by (Wang *et al*., 2015) [23]. The model of corrosion rate was developed and validated with indirect and direct data from a buried pipeline spanning 110 km. Tang *et al*., (2015) [22] worked on the effect of pH value on corrosion of carbon steel under an applied alternating current. The outcome showed corrosion rate of carbon steel increases as AC current increases and the corrosion rate decreases as the pH value increases in the alkaline end direction. Corrosion resistance of the welded joint of submarine pipeline steel with ferrite plus bainite dual-phase microstructure was investigated by (Wang *et al*., 2015) [23]. The results showcased that the base metal corrosion rate was more compared to the welded joint in terms of pitting and general corrosion. He *et al*., (2016) [8] studied the role of typical soil particle-size dietributions on the long-term corrosion behavior of pipeline steel. The observations proved that in the initial stage, the corrosion rate of X70 steel pipeline increased, at the intermediate stage it decreased, and in the final stage it increased. It was observed that both potential drops and surface roughness increases rapidly initially, then attained equilibrium state and finally stabilized as the concentrations of bicarbonate solutions increased in the study In-situ characterization of the early stage of pipeline steel corrosion in bicarbonate solutions by electrochemical atomic force microscopy conducted by (Li and Cheng, 2017) [15]. The influence of particle size on the long-term electrochemical corrosion behavior of pipeline steel in a corrosive soil was investigated by (He *et al*., 2017) [7]. The results by cathodic reaction proved that the corrosion rate of X70 pipeline steel increases as soil particle size decreases to less than 1.0 mm. Liu *et al*., (2019) [16] studied an ANN-based failure pressure prediction method for buried high-strength pipes with stray current corrosion defect. It was established that there is close agreement between the results of ANN model and full-scale experimental results both in accuracy and efficiency. Assessment of cathodic protection effect on long-distance gas transportation pipelines based on buried steel specimens was investigated by (He *et al*., 2020) [27]. It was observed that high degree corrosion was formed at the breaking point of anti-corrosive coatings even though the potential of cathodic protection is between -0.85 to -1.15 V. Du *et al*., (2020) [28] researched on corrosion rate assessment of buried pipelines under dynamic metro stray current. The results proved that many fluctuation periods spread between 50 - 200 s whereas the dynamic fluctuation periods are between 0 - 300 s.

The study of factors that influence corrosion of steel pipeline in soil will be very cumbersome because several factors are involve and at different levels. One approach to make the process easy and still maintain the integrity of results is the application of statistical methods. The statistical concept that derived application by many researchers for this type of study is the design of experiment (DOE) by Taguchi technique (Sadriwala *et al*., 2020) [19]. The Taguchi techniques uses an orthogonal array (OAs) to produce a small number of experiments by studying the entire space parameter (Yesilyurt and Cesur, 2020) [25]. In this technique factors are divided into controllable and noise factors (Joseph *et al*., 2023) [10]; factors that are created and controlled are called controllable factors while those that introduces deviations and difficult to control are known as noise (Karabas 2014) [11]. This technique uses signal to noise ratio (S/N) to scale down the negative effects of noise on the outcome and to perform the analysis of variance - ANOVA. S/N ratio is grouped into three criterions i.e., larger the better, nominal the better and smaller the better, the objective of each analysis determines which criteria to use (Kumar and Harsha, 2020) [14]. The S/N ratio makes it possible to perform optimization of parameter in the conducted research (Balcik and Unal, 2023) [2]. The Taguchi technique provides a pathway for design optimization, find solution with fewer number of experiments, thereby saving energy, time and cost. In the literature, Optimization of the electrolytic plasma oxidation processes for corrosion protection of magnesium alloy AM50 using Taguchi method was studied by (Ma *et al*., 2007) [18]. It was established that KOH concentration affected the corrosion resistance of coatings the most. Farzaneh *et al*., (2011) [6] optimized the corrosion performance of electroless Ni-P coatings using Taguchi method. The results showed that sodium dodecyl sulfate surfactant increases resistance to corrosion and enhances morphology of surface. Taguchi method for the optimization of pulsed current gas tugsten arc welding parameters for corrosion resistance of UNS S322760 super duplex stainless steel was investigated by (Yousefieh *et al*., 2011) [26]. It was found that pulse current was the main significant factor affecting corrosion resistance. Afrasiabi *et al*., (2014) [1] studied effect of heat treatment on the corrosion behavior of AA6061-T6 by Taguchi method. NaCl concentration was found to be the main influential factor affecting AA6061 corrosion resistance. Taguchi method optimization of corrosion protection parameters of steel pipeline was researched by (Zedin *et al*., 2016) [13]. The results proved that NaCl was the most influential parameter at 20wt%. Optimization of TIG welding process parameters for X70-304L dissimilar joint using Taguchi method was investigated by (Benlamnouar *et al*., 2019) [3]. It was observed that gas flow is the most paramount TIG welding parameter that affects characteristics of dissimilar weld. Kasman (2019) studied pin offset effect on the friction stir welding (FSW) via Taguchi-Grey relational analysis: a case study for AA 7075-AA 6013 alloys. The results showed that the fracture location of welded joints was between the AA 6013-base metal and heat affected zone, it was found on the heat affected zone. Corrosion behavior of SiC-Reinforced AI 6061/SiC metal matrix composites using Taguchi technique was investigated by (Sarapure et ai., 2020) [20]. It was established that monolithic aluminum 6061 alloy gave lower corrosion resistance when compared to composites. Balcik and Unal, (2023) [2] investigated the corrosion rate in X 65 steel pipes by Taguchi method based on factors originating from soil and external interactions. The results proved that the moisture content affected the corrosion rate more than other factors. Taguchi technique with smaller the better criteria was considered in this study to investigated the effects of control factors: pH, clay content and moisture content on the corrosion rate of buried API 5L× 70 steel pipeline of dimension (60×400×2 mm) in sampled soil samples. Regression models were developed to predict corrosion rate in terms of pH, clay content and moisture content. The percentage contribution of each parameter was evaluated using ANOVA statistical tool.

2. Materials and Methods

2.1 Experimental procedure

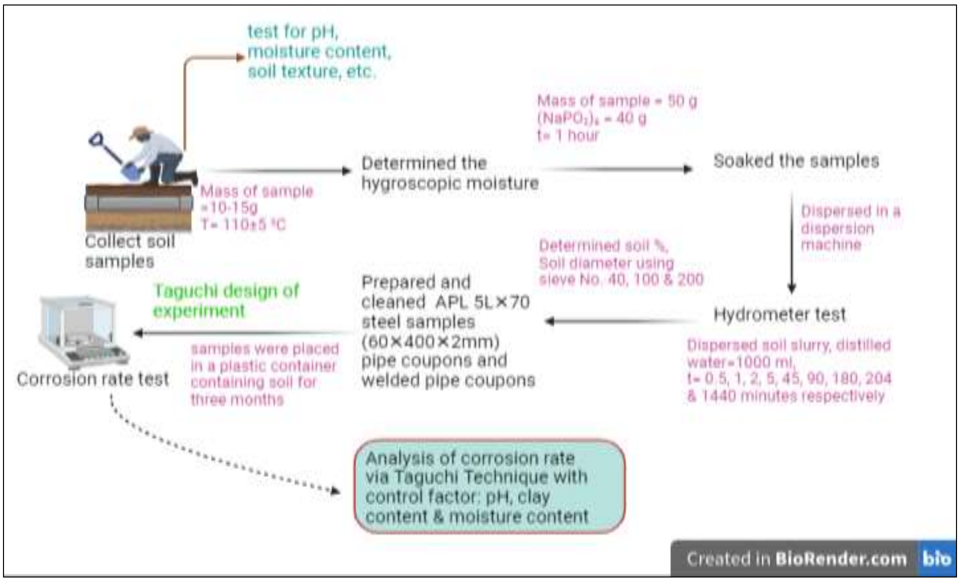

Fig 1: Experimental procedure

2.2 Control Parameters

For this study; previous preliminary studies identified three control factors and the ranges that tends to contribute to corrosion rate in the soil samples at the different locations. These factors are pH, clay content and moisture content. These factors were considered for the Taguchi design of experiment and their levels are shown in Table 1. L9 orthogonal array was designed with the aid of Minitab 22 software and presented in Table 2; the table has four columns namely experimental runs, pH, CC (%), and MC (%), each column showing 9 levels of combinations known as experimental runs. Corrosion rate was the response observed during the experiment.

Table 1: Control factors and their levels for Taguchi DOE

Parameters	Levels		
	1	2	3
pH	4	6	8
Clay content CC (%)	1	5	10
Moisture content MC (%)	20	30	40

Table 2: Taguchi L9 orthogonal array experimental layout with Minitab 22

Experiment runs	pH	CC (%)	MC (%)
1	4	1	20
2	4	5	30
3	4	10	40
4	6	1	30
5	6	5	40
6	6	10	20
7	8	1	40
8	8	5	20
9	8	10	30

2.3 Regression Equation

In this study, linear regression equation was used to model corrosion rate in terms pH, CC and MC. Expressing the dependent in terms of the independent variable in a multiple regression equation is given by (Joseph *et al.*, 2023) [1] in equation 1

$$z = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \cdots + a_nx_n \quad (1)$$

a_o to a_n denotes coefficients of linear equation and independent variables represented by x_1 to x_2, Z is the dependent variable. R-squared (R^2) and R-squared adjusted (Adj-R^2) were employed to decide the quality of fit for the linear model. Equations 2 and 3 were used to compute R^2 and Adj-R^2

$$R^2 = 1 - \left[\frac{SS_{residual}}{SS_{residual} + SS_{model}}\right] \quad (2)$$

$$Adj.R^2 = 1 - \left[\frac{\left(\frac{SS_{residual}}{df_{residual}}\right)}{\left(\frac{SS_{residual} + SS_{model}}{df_{residual} + df_{model}}\right)}\right] \quad (3)$$

Residuals represents volume of variation that cannot be explain by the response and model stands for the volume of variation explained by the model based on the general model test for significance.

2.4 Anova

Given the corrosion rate results, the percentage contributions of pH, clay content and moisture content by was determined by ANOVA statistical analysis.

3. Results and Discussion

3.1 Taguchi analysis of corrosion rate

Table 3: Mean and S/N Ratio of Corrosion rate

S. N.	pH	CC (%)	MC (%)	CR	
				MEAN ($mg/dm^2/yr$)	S/N (dB)
1.	4	1	20	0.043	27.3306
2.	4	5	30	0.045	26.9357
3.	4	10	40	0.050	26.0206
4.	6	1	30	0.043	27.3306
5.	6	5	30	0.045	26.9357
6.	6	10	20	0.050	26.0206
7.	8	1	40	0.043	27.3306
8.	8	5	20	0.045	26.9357
9.	8	10	30	0.050	26.0206
			Mean	0.046	26.7623

Table 3 shows the results of the mean corrosion rate (CR) in $mg/dm^2/yr$ and signal-to-noise (S/N) ratios. The smaller the better optimization criteria were used to evaluate the S/N ratio. The combination of control factors with the most impact (i.e., lowest corrosion rate of 0.043 $mg/dm^2/yr$) was seen when CC was 1%, pH ranging from 4-8, and MC ranging 20-40%; i.e., run 1,4 and 7. It was observed the S/N ratio at these runs were 27.3306 dB; i.e., 0.5683 dB higher than the general S/N ratio mean 26.7623 dB. This is an indication of significant deviation.

Table 4: Corrosion rate response table

Level	pH	CC (%)	MC (%)
	S/N CR (dB)	S/N CR (dB)	S/N CR (dB)
1	26.72	27.33	26.72
2	26.76	26.94	26.72
3	26.76	26.02	26.72
Delta	0.00	1.31	0.00
Rank	2.5	1	2.5

Delta is the difference between the highest and lowest S/N ratios of the response for each level of the factor. The delta values indicate the relative effect of each factor on the response. The factor with the highest effect is rank 1 and so on. From Table 4; It was observed that clay content (CC) has the highest Delta value of 1.31 dB and hence it is ranked 1 as being the most influential parameter compared to pH and MC. This observation is in agreement with Table 3 as CC remain constant while pH and MC can vary in order to get minimum corrosion rate.

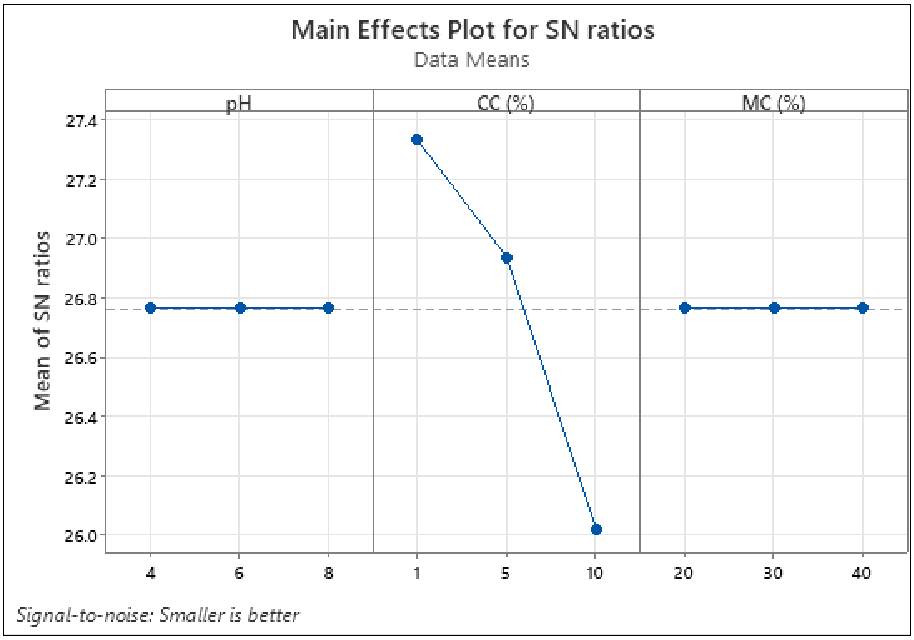

Fig 2: Main effect plots for S/N ratios of corrosion rate

Figure 2 shows that the clay content (CC) has the highest main effect on the corrosion rate compared to pH and MC. On average the experiment with 1% CC had the greatest S/N ratio with respect to the S/N mean compared to 5% and 10% as shown in the CC main effect plot. This observation is in tandem with the response Table 4 and corrosion rate in Table 3. They all agree that 1% CC gives the minimum corrosion rate regardless of the variation in pH and MC. This agreement is further supported by the main effect plot of pH and MC whereby the graph remains horizontal on the mean. This implies varying those factors has little or no effect on the corrosion rate.

The regression equation is given as

$$CR\left(\frac{\frac{mg}{dm^2}}{yr}\right) = 0.0418 - 0.00000pH + 0.000787\,CC\,(\%) + 0.000000\,MC(\%) \quad (4)$$

From equation 1, it can be seen that pH has a negative coefficient implying that corrosion rate decreases with increasing pH even though the coefficient is zero, a positive coefficient of CC shows that corrosion increases as CC increases. Though the coefficient of MC is zero, it might suggest that MC might not have a statistically significant effect on corrosion rate. However, moisture can still play a role in corrosion because it is negative. This regression equation is consistent with the main effect plots in Figure 2.

Table 5: Regression analysis model for corrosion rate

Predictor	Coef	SE Coef	T	P
Constant	0.041803	0.001282	32.60	0.000
pH	-0.00000000	0.0001431	-0.00	1.000
CC (%)	0.00078689	0.00006349	12.39	0.000
MC (%)	0.00000000	0.00002863	0.00	1.000

R-Sq = 96.8% R-Sq (Adj) = 95.0%

The general regression analysis in Table 5 shows that clay content (CC) has a statistically significant positive effect on corrosion rate, while pH and MC within the studied range do no show statistically significant linear effects according to this model. This does not mean they do not influence corrosion, other factors not considered might overshadow their effects or maybe they have complex relationship with the rate of corrosion. The R-Sq = 96.8% means the model explains appropriately 96.8% of the variation in the response. R-Sq (Adj) = 95.0% implies the model correctly explains the data by 75%. The outcome of regression analysis concurs with observation in the main effects plots in Figure 2 and the response table 4.

Table 6: ANOVA table for regression model

Source	DF	SS	MS	F	P
Regression	3	0.000075541	0.000025180	51.20	0.000
Residual Error	5	0.00002459	0.000000492		
Total	8	0.00007800			

Table 6 shows the analysis of variance for the regression model of corrosion rate of an underground pipe consisting of three level of pH, three levels of CC, and three levels of MC. This finding further support that the regression model in equation 1 (with pH, CC, and MC as predictors) is statistically significant for predicting the corrosion rate. This is because $p<0.05$ and F=51.20, indicating that the model can explain a significant portion of the variation in corrosion rate compared to the unexplained variation. This analysis further supports the regression model equation 4.

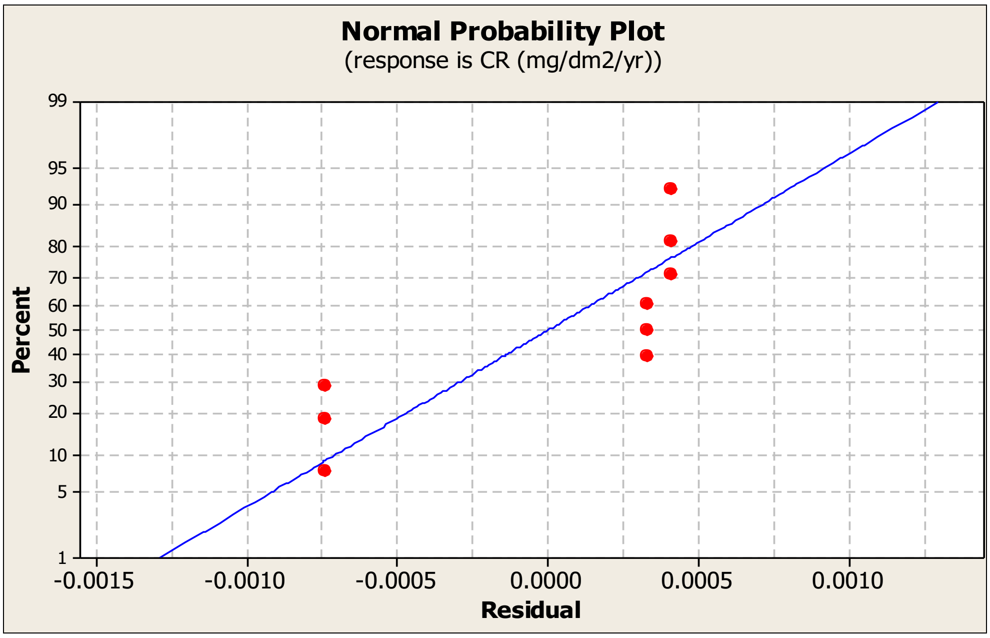

Fig 3: Normal probability plot

Figure 3 shows the normal probability plot used to assess the normality of corrosion rate, that is the response variable for the different values of control factors pH, clay content (CC), and moisture content (MC). From the plot, the points do not fall close to a straight line, this suggests that the residuals are not normally distributed. This can be attributed to a nonlinear relationship between the control factors and the response.

4. Conclusion

Taguchi technique experimental design was employed in this study to investigate the parameters that enhances corrosion of buried API 5L× 70 steel pipeline in soil. The parameters considered in this study are pH, clay content (%), and moisture content (%). Based on the results of experiment and analysis, the following conclusions can be drawn; clay content was found to have a significant influence on corrosion rate, while pH and moisture content have similar little or no effect on the corrosion rate, based on the range considered. The optimized parameters for minimum corrosion rate are clay content 1 wt %, pH 4-8 and moisture content 20-40 wt %.

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