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Evaluation of Corrosion Rate in X 65 Steel Pipes by Taguchi Method Based on Factors Originating from Soil and External Interactions

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Steel pipelines that are used for the transportation of natural gas and petroleum usually pass through different places with different soil characteristics. Due to distinct soil structures and other corrosive factors, pipelines tend to corrode at different rates. In this study, the effects of moisture content, salt concentration, pH, AC potential and cathodic protection levels on the corrosion rate were investigated as factors affecting corrosion in steel structures originating from the ground and external sources. The number of experiments to be carried out was decided as a result of experimental design with the Taguchi statistical method. L16 orthogonal array was used for 4 different levels of 5 corrosion rate affecting factors and 16 different experimental studies were conducted to obtain corrosion rate values for each experiment. Based on the statistical analysis results, the effect of changes in moisture content of the soil on corrosion rate was higher compared to other factors. Considering that underground pipelines usually pass through neutral environments (pH levels between 6-8), the effect of changes in pH value on corrosion rate is less than the other factors studied. In addition, with the regression analysis performed through the Minitab software, a linear regression model and an equation was created to calculate the corrosion rates. Corrosion rate results obtained with the regression equation were compared with the test results performed in different test environments. By calculating the corrosion rate for different factors, selection of or changing the pipeline route, selection of material wall thickness, planning of pipeline control and maintenance periods can be made in the most ideal way. Also, a comparison of corrosion rates against existing literature shows that corrosion rates of steel materials change between outstanding classification ranges according to corrosion resistance classification of steel materials.

Key words: corrosion rate, steel pipeline, soil characteristic, statistical analysis, experimental.

1. INTRODUCTION

Buried steel pipelines are usually used in the transportation of natural gas and petroleum products and they are exposed to factors that cause corrosion. These pipelines are coated with protective material to maintain their integrity. Corrosion is higher at places where coating damages exist and when exposed to different corrosive factors. While the corrosive environment of the soil is the main reason for pipeline corrosion, environmental factors such as moisture content, pH value, salt concentration, temperature, microorganisms, etc. also affect the external corrosion process of buried steel pipelines. Many factors originating from the soil environment affect the external corrosion process in varying degrees, making the corrosion process more complicated. Calculated corrosion rates on buried steel pipelines change due to the variability of the moisture content. Especially in the winter and spring seasons, corrosion rates are more dependent on the moisture content of soil compared to other seasonal periods. The change in the moisture content of the soil makes it difficult to determine the corrosion process that occurs between pipe surface and soil [1, 2]. Water content in the soil environment is important for the ionization of the oxide layer on the metal surface and the ionization of the electrolyte on the metal structure, so electrochemical cells required for the initiation of corrosion activity are formed. Gupta and Gupta [3] conducted comprehensive research about the effect of soil moisture content on the corrosion rate of buried carbon steel. Corrosion tests were carried out with low carbon steel coupons in soil samples. The corrosion rate of carbon steels was calculated after six months at constant moisture content and a close relationship was determined between mass loss and moisture content. In another study, the corrosion behavior of X 60 steel in soil samples taken from three different regions was investigated by Noor and Al-Moubaraki [4]. It was found that corrosion current densities of X 60 steels increased depending on the effect of the soil's moisture content.

The pH value of soil environment typically ranges from 3 to 10 and the removal of alkali ions such as calcium, magnesium, sodium and potassium from the soil due to rainwater and dissolving carbon dioxide into groundwater make mineral soil acidic. It is also stated that the pH value of the soil environment is not a strong indication of the steel structure corrosion alone, but low pH levels become effective when combined with other corrosive factors [1, 2]. American Water Works Institution carried out a project to estimate the remaining life of pipelines in which corrosion rates of cast iron pipes were calculated in different pH conditions [5]. Although this study did not yield a correlation between pH value and pipeline corrosion, pH was accepted as a factor affecting soil corrosivity. In another study, Ismail et al. [6] concluded that pH range of soils usually vary from 5 to 8 and under these conditions, the corrosivity of the soil is determined by factors other than pH. The salt concentration in the environment is another factor for corrosion that is often associated with the presence of chloride ions. Anodic dissolution reactions that occur on

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metal surfaces are accelerated by chloride ions. Geological processes and the application of salt to the highways for icing prevention are the main sources of chloride ions in the soil environment. Furthermore, chloride ion levels are dependent on the moisture content of soil [7]. Also, long term effect of salt concentration on corrosion of carbon steel was investigated. The corrosion behaviour of carbon steel in 3 % NaCl solution was studied and corrosion rates were measured with electrochemical impedance spectroscopy. It was concluded that at a 3% concentration level, corrosion accelerates until the rust layer prevents more oxygen diffusion and after the corrosion process begins to decelerate [8].

Alternating Current (AC) interference is another phenomenon that affects the corrosion process of steel materials. AC-related corrosion problems are usually observed in regions where high-voltage transmission lines are commonly found. AC induced corrosion problems in coated pipelines are critical compared to bare pipelines due to the localization of corrosion on defect areas that lead to high-induced AC current densities [9]. When AC potential and current values at pipelines are higher than the criteria specified in ISO 18086, the AC interference level is considered unacceptable [10]. Jiang et al. [11] examined the effect of AC interference on the corrosion process of Q235 steel pipeline with corrosion coupons ranging from 20 x 20 mm to 80 × 80 mm in soil environments. AC interference caused output of Direct Current (DC) on the damaged areas of coatings and this current flow induced corrosion on relatively small, damaged areas due to the initiation of metal dissolution reactions. Cathodic protection has been defined in BS ISO 15589-1:2015 standard [12] is a main corrosion control method for steel materials as a protection ionic currents flow from anode beds and reduce the corrosion process that occurs on damaged areas of coating. One of the ways to determine the effect of cathodic protection on oilfield steel pipeline corrosion is to perform field experiments. Continuous observations on pipe thickness during cathodic protection were examined [13]. The carbon steel pipeline was cathodically protected at appropriate levels through the application of a galvanic anode system during the construction period. Metal wall thickness was also observed with ultrasonic thickness measurements for 18 months and the worst defect was determined as 0.23 % wall loss. This shows that the technical integrity of the new pipeline which is maintained with low wall corrosion loss is supported using a galvanic anode system during the construction period. Furthermore, the impressed current system is more appropriate than the galvanic anode system for long term pipeline operations.

The application of factors affecting the corrosion rate of steel structures with different levels and combinations requires a large number of experimental studies. In this case, statistical analysis methods can be used to reduce the number of experiments. One of the most widely used statistical methods for this context is experimental design with the Taguchi method. The optimal levels of the parameters affecting experimental design can be determined with a relatively small number of experimental studies with this method. The Taguchi method is an ideal method to find the most suitable combination within different levels of different factors. The main purpose of the Taguchi method is to minimize the sensitivity to external factors that may affect the process while determining the most ideal process conditions [14]. In the Taguchi method, the ratio between the signal and noise factors of analysed data expresses the efficiency of the study, and the application success of the method increases if the noise ratio is low [15]. Also, in the method, orthogonal arrays are used to reduce the number of experiments when many experiments are required for each different level of the studied factors [16]. The Taguchi method is especially preferred in experimental studies where corrosion research takes a long time. In the research of corrosion processes occurring between galvanic couples in the welding area of metals, the Taguchi method was used for reducing the number of experiments [17].

In another study, the effects of salt concentration, temperature, and solution velocity on the corrosion rate of steel structure were researched using the Taguchi method with an L9 orthogonal array [18]. In the literature, corrosion processes caused by the ground or the external interaction of the steel material were examined separately. Also, simultaneous effects of a small number of factors on the corrosion rate were researched in previous experiments. There were limited studies in which statistical analysis methods were applied and further, the number of examined factor levels remained limited in these studies.

In the current study, the effects of five factors arising from soil conditions and external sources on the corrosion process were examined together in an experimental environment. By bringing the soil environment from the regions where the pipelines pass, it was ensured that the conditions in the field were created in the experimental environment. During the study, the main factors affecting the corrosion of the steel pipeline were applied at different levels in a controllable test environment, and the corrosion rates were measured. Factors at different levels were applied simultaneously to the pipe that was placed in the soil environment at room temperature and the corrosion rates were determined with the corrosion coupons attached to the pipe. Measuring corrosion rates with corrosion coupons under laboratory conditions is a convenient method in terms of the controllability of test parameters. Considering the number of factors and factor levels examined in the study, the L16 orthogonal array was chosen in the Taguchi method. With the regression analysis performed through the MINITAB 17.3, a linear regression model and an equation for the corrosion rate contingent upon five factors were created. Corrosion rates that were calculated with the regression equation, which was derived from the regression model, were compared with the test results performed in different soil conditions. In addition, the results of all corrosion rates were compared according to the corrosion resistance classification of ferrous materials [19]. The resistance ranges of the steel against corrosion were determined depending on the varying parameters and their levels.

2. EXPERIMENTAL WORK

2.1. Design of experimental environment

The experimental setup to determine the corrosion rate of steel pipes was established inside the Turkish Petroleum Pipeline Corporation (BOTAS) facility in cooperation with

Baskent University. The setup was designed to measure a corrosion rate change with the selected factors (Fig. 1). An isolated glass protected soil pool with dimensions 2 m × 1.5 m was produced and a steel pipe of 4 inches in diameter and 1 meter in length was placed inside. Soil pH level, moisture content, salt concentration, AC potential and cathodic protection were selected as reference factors to measure the corrosion rate of carbon steel.

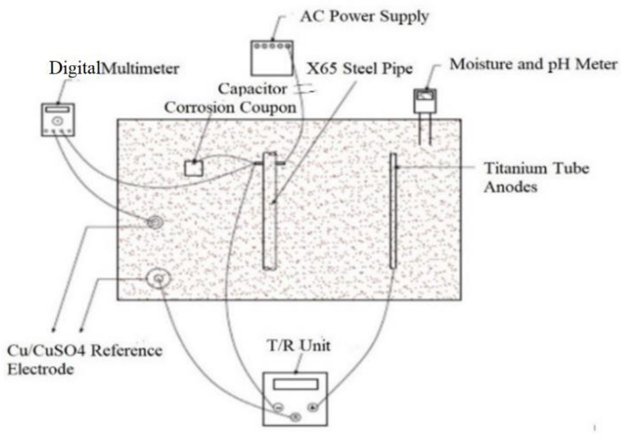

Fig. 1. Schematic demonstration of experimental setup

Corrosion coupons that had the same chemical composition as steel pipelines used for natural gas transportation in Turkey were prepared to measure the corrosion rate of carbon steel (Table 1). The corrosion coupons were cut precisely in size of 40 × 40 × 7 mm and their surface areas were checked with a vernier caliper. After the cutting process, fine grit sandpaper was used to achieve smooth surfaces of coupons; in addition, the coupons were cleaned with pure water and acetone to avoid any roughness or residue. Prepared coupons were also completely dried with air. Before the experiments, weight measurements of coupons were performed using an electronic scale with an accuracy of 0.001. Weight measurements for each coupon were repeated 10 times and average values were recorded.

The prepared corrosion coupons were connected to a fabricated polyethylene coated steel pipe using connection cables. Pictures of corrosion coupons before and after experiments showing in Fig. 2. The pipe was undamaged, and it was not used in the field before the experiment. The connection cable was mounted to corrosion coupons. Additionally, the contact end of the connection clip was painted to prevent it from the corrosion process. The steel pipe and connected corrosion coupons were both immersed approximately 30 cm deep in reference soils that were obtained from different regions nearby Ankara (Turkey). Pre-tests were performed to determine the appropriateness of the soil so that the selected soil would produce corrosion rate results near outstanding corrosion resistance classification. After pretesting, the selected soil environments were sent for analysis to determine characteristics, which were also verified with the prepared setup (Table 2). Some parameters that existed in the soil environment such as magnesium, calcium, electrical conductivity, chloride and sulfate ions of the soil were also analysed but not followed in the current experimental studies. The pH level, moisture content and salt concentration of the selected soil environment became the reference factors for the study. The pipe that was immersed in soil environments was exposed to different levels of corrosion affecting factors and corrosion rates were calculated by using corrosion coupons.

Table 1. Chemical composition of X65 steel

	C, %	Si, %	Mn, %	P, %	S, %	V, %	Nb, %	Ti, %
X 65	0.16	0.45	1.65	0.020	0.010	0.09	0.05	0.06

Fig. 2. a – corrosion coupon prepared for experiment; b – corrosion coupon connection; c – corrosion coupon used in the experiment before cleaning process; d – corrosion coupon after cleaning process

Table 2. Analysis of soil environment

Analysed parameters	Units	Analysis results	Analysis methods
Soil moisture content	%	0.5	AOAC 2000
pH level	–	7.92	Mt 5.4.2. T 55 in saturated soil paste
Electrical conductivity	ds/m	0.16	TS ISO 11265
Salt concentration	%	0.0036	TS 8334
Calcium	ppm	4.04	Can be extracted
Magnesium	ppm	1.88	Can be extracted
Sulfate	me/L	1.98	Gravimetric
Chloride	me/L	4.11	Titrimetric

In the test environment, applied cathodic protection levels were chosen between -800 mV and -1500 mV CSE (-720 mV and -1420 mV SCE) in congruence with the criteria of BS ISO 15589-1: 2015 [12] standard and the operational conditions of natural gas pipelines in Turkey. An automatic/manual adjustable rectifier unit (50 Volt/20 Amperes), mixed metal oxide titanium tube anode (1.6 cm × 50 cm) and fixed type copper/copper sulfate ($Cu/CuSO_4$) reference electrode were placed in the soil environment for installation of the impressed current cathodic protection system. The reference electrode was placed on the opposite side with respect to the pipe in the soil pool for the application of stable cathodic protection potentials. The negative pole of the rectifier unit was connected to the pipe and the positive pole was connected to the titanium tube anode. Also, a fixed type $Cu/CuSO_4$ electrode was connected to the reference output of the rectifier to measure the applied potential correctly. Cathodic protection levels were adjusted on the rectifier unit and after the potential fluctuations of the pipe were stabilized, the experiments were performed. Also, a portable type reference electrode was embedded inside the soil environment to verify and record potential measurements throughout the experiments. The tip point of the reference electrode was moisturized with water for minimizing ground resistance and ensuring measurement clarity.

AC power supply, which had a capacity of 50 V/50 A and different potential setting ranges between 0 and 50 V, applied AC potentials directly to the pipe in the soil pool. The phase part of the power supply was connected to the pipe and the earth part was attached to the copper plates that were embedded in a separate area from the experimental environment for grounding. AC potential range used in the test environment was chosen by considering minimum and maximum measured levels in the field conditions, and hence corrosion rate measurements were performed for selected AC potentials between 0 and 40 volts. The AC power supply and the pipe were connected with a 50 V/1000 µF capacitor to protect the DC cathodic protection currents from the interference of the AC power supply. AC currents passed from the pipe to the corrosion coupons were also measured via a high internal resistance voltmeter. The measured AC currents were then divided into the surface area of the coupons for assessment of corrosion risk depending on the AC current density. The moisture content of the soil was another factor that was tested in the experimental environment for carbon steel corrosion. Corrosion rates were calculated after the application of different moisture levels between 0.5 % and 10 %. The lowest limit value of moisture content, which also was one of the main criteria for determining the soil from alternatives, was taken from reference soil under dry conditions whereas the highest limit value was chosen by considering the moisture content of wet soil in field conditions. Before the start of each experiment, moisture contents of soil were determined precisely by weighing the soil samples before and after the drying process in an oven at 105 °C for 2 hours [20]. The level of soil moisture content was determined from the loss of mass between two weightings with the help of Eq. 1:

$$Mc = \left(\frac{M_{(\mathrm{ms})}}{M_{(\mathrm{ds})}}\right) \times \%100, \quad (1)$$

where M_C is the moisture content, $M_{(ms)}$ is the mass of moist soil and $M_{(ds)}$ is mass of dry soil.

The moisture content was monitored six-hourly with a moisture content device with ± 0.1 precision, while it was calculated every 24 hours through equation 1. Being closed in the working environment is a partial solution against the factors that can change the moisture content. When a change in moisture content was detected during the experiment, necessary adjustments were made by adding water or drying to reach the desired soil moisture content.

The studied salt concentration levels of soil were selected from 0.0036 % to 3.5 %. Among the soil samples that were taken from the Ankara region, selecting a soil sample with the lowest salt concentration was another criterion for the reference soil. To obtain the lowest salt concentration level, soil samples were taken from pipeline regions away from highways and salt fields. The maximum level of salt concentration was selected as 3.5 % due to reports that the corrosion rate reaches its maximum value with this specified salt concentration and if exceeded, the corrosion rate begins to decrease up to a certain value [21]. The salt concentration of the soil environment was changed before experimentation by adding sodium chloride and pure water mixture to the soil for ensuring homogeneous distribution. After the adjustment of salt concentration, the drying process was applied to the soil until the desired moisture content level was achieved.

Furthermore, pH levels ranging from 3 to 10 were selected to understand the effect of changes in pH on carbon steel corrosion. These pH limits were determined based on a review of published literature together with field experiments that revealed maximum and minimum pH levels in Turkey through characteristics of soil/pipe interface [2]. To obtain low pH levels below 6, an acetic acid solution (5 % by mass) was added to the reference soil environment. Levels between 6 and 10 were reached through the addition of buffer solutions containing appropriate pH levels into the soil environment before testing. The mixtures for adjusting pH were used in low quantities and followed by a short-time drying process. When necessary, this sequence was repeated to ensure the moisture content and the pH levels of the soil where at their desired values. The soil pH levels in the vicinity of the pipe and corrosion coupons were monitored with a pH meter (Hanna brand) that had a sensitivity of +/- 0.01. These were recorded every 30 minutes during testing. All experiments were conducted for a week and the corrosion rate was determined from coupons taken out from the connected pipe. Cleaning of the corrosion coupon surface was done according to ASTM G-1-03 "Corrosion products cleaning method" standard before weight loss measurements [22].

2.2. Application of the Taguchi method

Moisture content, salt concentration, pH, cathodic protection and AC potential, which are variables that affect the corrosion process in natural gas pipelines originating from the ground or caused by external interactions, were examined in the experimental design with the Taguchi method. The studied factors and their levels are shown in Table 3. The matrix structure suitable for the experimental design consisting of 5 different factors was determined according to the number of factors and their levels as entered in the Minitab software. The most appropriate Taguchi experimental design for the 5 factors and 4 levels was formed with the L16 orthogonal array (Table 4). Also, total degrees of freedom are considered for the selection of the orthogonal array [23].

The degree of freedom for each factor studied is expressed as one less than the number of factor levels, and the total degree of freedom can be one less than the number of total experiments. In this case, the degrees of freedom for each factor studied was determined as 3, which is one less than the number of factor levels, and the total degrees of freedom became 15 which confirms that the L16 orthogonal array should be used. During the experiments, the factor levels were measured and monitored periodically so that changes in levels would not affect other factors. In this way, it was ensured that the factors remained independent by not affecting each other.

In the Taguchi experimental design, the concept of Signal/Noise (S/N) ratio is used to reduce the effect of uncontrollable factors in experiments performed at different factor levels. Using this ratio, it is aimed to reduce the sensitivity of controlled factors to uncontrolled factors. S/N ratio is also defined as the mean divided by the standard deviation and in the Taguchi experimental design, 3 different S/N ratio definitions, which are the smallest best, largest best and nominal best, are used [24, 25]. Minimization of corrosion processes occurring in pipelines is a desirable condition for prolonging pipeline operation time and reducing maintenance-repair costs. For this reason, while determining the S/N ratios before the study, it was assumed that the least level of the corrosion affecting factors was the best situation in terms of preventing the corrosion process and the S/N ratio was determined as the smallest best.

2.3. Application of regression analysis

Regression analysis is a method that models and analyses if there is a relationship between different variables and a dependent factor or more than one independent variable [26]. Regression analysis was performed with the Minitab software, version 17.3.1, to determine the most and least effective factors on corrosion rate among the studied factors and to observe the probability (P) values of each factor. Those with probability values less than 0.05 are considered to be effective on the test result at the 95 % confidence level [27]. In addition, a linear regression equation was created to calculate the corrosion rate that occurs when 5 corrosion affecting factors are combined. The corrosion rate values which were calculated as a result of the experimental studies were compared with the corrosion rate values calculated with the help of the created equation. The soil in the experimental environment that was created for the comparison of corrosion rates was brought from different regions of Turkey, where pipeline corrosion processes are common. The soil analysis data of the experimental environments, the applied cathodic protection and AC potential levels are shown in Table 5.

Table 3. The factors and levels examined in Taguchi experimental design

Factors	Unit	Level 1	Level 2	Level 3	Level 4
Cathodic protection	mV	-800	-1100	-1300	-1500
Salt concentration	%	0.0036	1	1.5	3.5
AC potential	V	2	10	20	40
Soil moisture content	%	0.5	3	5	10
pH	–	3	5	7.92	10

Table 4. L16 orthogonal array

Experiment number	Cathodic protection level	Soil salt concentration	AC potential level	Soil moisture content	pH level
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	3	1
16	4	4	1	3	2

Table 5. Test environments where the regression equation and field studies are compared

Factors	Units	Field soil 1	Field soil 2	Field soil 3
Cathodic protection	mV	-900	-1300	-1100
pH	-	8.18	9	8.79
AC	V	40	10	20
Salt concentration.	%	0.0122	0.0036	0.0201
Soil moisture	%	1.24	0.5	0.56

3. RESULTS AND DISCUSSION

Corrosion rates were calculated by weighing the corrosion coupons before and after the experiments and converting weight loss values to corrosion rate through Eq. 2:

$$R_{corr} = \left(\frac{87.6\,W}{DAT}\right), \quad (2)$$

where R_{corr} is the corrosion rate in mm/year, W is weight loss in mg, D is density of specimen in g/cm^3, A is an area of coupon in cm^2, T is test time in hour respectively.

Although the dimensions of the corrosion coupons are the same, to calculate the coupon surface area in equation 2, the coupon sections were determined by measuring separately with a caliper, so that possible changes in dimensions that may occur while preparing the coupon were considered.

The experiments were carried out in the reference environment based on the orthogonal array which is given in Table 4. The average corrosion rates and standard deviations, which were obtained by repeating each experiment 3 times, are shown in Table 6. According to the corrosion rates in the orthogonal array, the highest corrosion rate was calculated as 0.320 mm/year which is at the "good" level based on the corrosion resistance classification of ferrous metals. At the lowest corrosion rate (0.041 mm/year) the corrosion resistance is at an “excellent” levels. All corrosion rate values calculated as a result of the experiments are at "good" and "excellent" resistance level. In addition "weak" and "unacceptable" levels could not be reached in the environment where the experiments were carried out. It is considered that it is possible to see these levels if the experiments were carried out in a salty water environment instead of soil or by changing the amounts of other factors that affect the corrosion rate, not examined within the scope of this study.

In addition, the S/N ratios for the smallest best are shown in Fig. 3 for each studied factor level. The contributions to the corrosion rates and probability values of the studied factors are shown in Table 7. According to the S/N graphs created with the Taguchi statistical analysis method, the lowest corrosion rates occur when the cathodic protection level is -1500 mV, soil salt concentration is 0.0036 %, AC potential is 2 V, the soil moisture content is 0.5 % and the pH value is 10. When the contribution rates of the factors to the corrosion rate are examined, it is seen that the effect of soil moisture content on the corrosion rate is the highest and the pH factor is the least. In addition, considering the probability values (P), the probability of the pH level is found to be greater than 0.05 which shows that among the studied factors and levels, only the pH factor is statistically ineffective in the experimental results. In the literature, it is stated that there is a close relationship between the moisture content of the environment and corrosion rate, and corrosion will increase rapidly as a result of increasing moisture [3]. In this case, the high effect of moisture content on corrosion rate from our experiments shows congruence with available literature. Additionally, the result of the minimum effect of the pH factor on the corrosion rate is also compatible with the evidence base where the pH does not have a direct effect on the corrosion rate and can only be effective in the formation of corrosion together with other factors [1, 6].

The compatibility of the corrosion rates found as a result of the experiments with the regression model is shown in Fig. 4. Experimental corrosion rates and fitted corrosion rate values are largely close to each other. Also, the competence of the regression model can be verified by using the regression spread range [28]. This range (R-Sq) is 89.2 % for experimental corrosion rate results whereas adjusted R-Sq is 88.5 %.

Table 6. Calculated corrosion rates and standard deviations based on the L16 orthogonal array.

Cathodic protection, mV	Salt concentration, %	AC potential, V	Moisture content, %	pH level	Average corrosion rate, mm/year	Standard deviation, mm/year
-800	0.0036	2	0.5	3	0.125	0.009
-800	1	10	3	5	0.155	0.009
-800	1.5	20	5	7.92	0.178	0.015
-800	3.5	40	10	10	0.320	0.035
-1100	0.0036	10	5	10	0.060	0.013
-1100	1	2	10	7.92	0.150	0.020
-1100	1.5	40	0.5	5	0.134	0.019
-1100	3.5	20	3	3	0.122	0.012
-1300	0.0036	20	10	5	0.127	0.014
-1300	1	40	5	3	0.140	0.013
-1300	1.5	2	3	10	0.047	0.011
-1300	3.5	10	0.5	7.92	0.065	0.009
-1500	0.0036	40	3	7.92	0.071	0.009
-1500	1	20	0,5	10	0.041	0.008
-1500	1.5	10	10	3	0.171	0.010
-1500	3.5	2	5	5	0.107	0.014

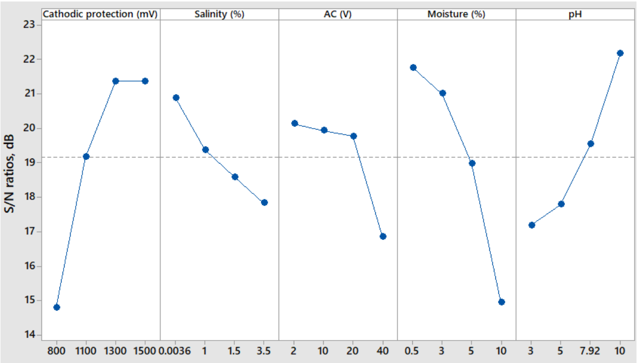

Fig. 3. Main effects plot for S/N ratio

Table 7. Regression analysis results

Studied factors	Contribution to corrosion rate, %	Probability
Cathodic protection	31.64	0.0002
Salt concentration	9.53	0.0140
AC potential	11.62	0.0080
pH	1.99	0.2040
Moisture content	34.46	0.0001

These ratios proove that the fitted corrosion rates with the regression model are close to the rates measured in the experimental environment. Furthermore, the average corrosion rates calculated as a result of the experiments which were repeated 3 times in different field soils and the corrosion rates calculated with the help of the linear regression model are compared for confirmation and the results are shown in Table 8. The corrosion rate calculated as a result of the experiments carried out in the field soil 2 environment close to these levels constituted the lowest corrosion rate obtained in all the experiments. It is understood that these factor levels are close to the ideal found with the Taguchi analysis, and should be taken into account while determining pipeline routes. The highest difference in corrosion rate, both in value and proportion, was determined between the field soil-3 experiments and the corrosion rates calculated with the regression equation. When the field soils are compared with the reference, it is seen that the greatest difference in field soil-3 environment is in salt concentration, compared to the others. It is considered that the reason for the high error is due to the different mineral and compound content that creates this salt concentration and affects the salt concentration of the soil environment [29].

Also, the difference between corrosion rates calculated with the regression equation and corrosion coupons in field conditions is realized as 0.018 mm/year at most. The difference between the corrosion rates is not at a level that can cause a change in the corrosion resistance classification. In addition, according to another study that created regression models and compared them with the experimental results, it is stated that the linear regression model, which is created to predict the ideal PET/PVP fiber diameters, gives closer values to the experimental results. Also, it is stated that applications of the Taguchi experimental design and linear regression model together create the most ideal combination for their study results [30]. Similar to previous literature, the corrosion rates calculated with linear regression and calculated as a result of the experiments are of equal importance in terms of corrosion risk assessment in pipeline operation.

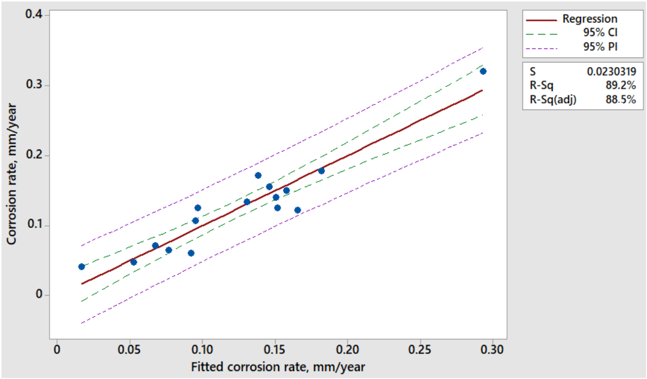

Fig. 4. Representation of corrosion rate results on linear regression model

Table 8. Comparison of the corrosion rates calculated in different experimental environments with the rates calculated with the regression equation

Corrosion rates, mm/year	Field soil 1	Field soil 2	Field soil 3
Calculated with linear regression	0.132	0.016	0.063
Calculated with corrosion coupons in the experimental environment	0.133	0.017	0.045
Standard deviations of corrosion rates in experimental environment	0.012	0.005	0.013

In the existing literature, the risk of corrosion occurring in the material is correlated with the AC current density values measured on the steel while examining the effects of AC interaction on the corrosion rate of steel materials [10, 11]. Evaluation of AC corrosion risk in natural gas pipeline operations in Turkey is made considering AC current density and AC potential values together over the pipeline. For this reason, both values are taken in all experimental studies. It is determined that AC current density values change between 1.6 A/m^2 and 80 A/m^2 when the AC potential measured over the pipe is kept constant at 40 volts during the experiment. The current density value of 1.6 A/m^2 is determined when the moisture content of the soil is 0.5 % and 80 A/m^2 is determined when the moisture content is 10 %. An increase in soil moisture content causes a decrease in soil resistance and in soils with low resistance; there is an increase in AC currents passing from the pipe to the corrosion coupon. It is also stated in studies that high AC current densities are measured in environments with low ground resistance [31]. For this reason, the relationship between the AC current density and soil moisture content obtained as a result of the study is in accordance with the literature. There is a corrosion risk if the AC current density value measured on the corrosion coupon for a certain period (such as 24 hours) is 30 A/m^2 or more based on ISO 18086 standard [10] which classifies the corrosion risk that occurs as a result of the AC interaction in steel materials. Considering this standard, AC corrosion should be evaluated in an environment with 40 volts AC and 10 % moisture content, where 80 A/m^2 is observed. However, there is no risk of AC corrosion in the case where the AC potential value measured on the pipe is the highest (40 volts) but the moisture content of the tested soil is the lowest (0.5). AC levels of 30 A/m^2 and above, which are considered critical in terms of corrosion risk can be reached by increasing both the moisture content and applied AC potential under the reference test conditions.

During the experimental studies, different buffer the solutions were used to adjust the pH value to required levels. Although the solutions used brought the pH values to the desired working levels, they also changed the moisture content of the soil before the experimental study. This is seen as a problem especially when the moisture content of the soil should not be changed while adjusting the pH level. In this study, it was attempted to address this by the application of short-term drying in the environment before the experiment. In doing so, changes in the soil moisture content had a limited effect on the soil pH value. Keeping the moisture constant throughout the experiment ensured that the pH value remained constant.

Although the effect of moisture content, salt concentration and pH level on the corrosion rate was investigated during the experimental studies, there are also different factors such as magnesium, calcium, sulfate and electrical conductivity that affect the corrosiveness of the soil environment. While analysing the studied soil environment, the levels of these factors were also found, but the effect of these factors on the corrosion rate was not investigated through our experiments. The levels of these factors were determined to form the basis for future studies on other factors affecting soil-borne corrosion.

4. CONCLUSIONS

Corrosion rates for X 65 steel pipes under field conditions were measured for the change of five different factors in soil samples taken from different regions in a controlled experimental environment. The corrosion rate estimations as a result of variations in the studied factors were made using the regression analysis and the following conclusions could be deduced:

It was observed that among the factors studied, soil moisture content affected the corrosion process in steel pipelines the most. In addition, the effect of cathodic protection on pipeline corrosion was close to the effect of moisture content. AC interference and soil salt concentration affected pipeline corrosion rate at the same level but fell below moisture content and cathodic protection. Considering that the pH values in the routes where the pipelines pass are generally in the range of 5-8, the pH effect on the pipeline corrosion was the least.

Although the effect of AC interference on steel corrosion was less than the moisture content of soil and cathodic protection, greater AC current output occurs from coating damage on pipelines passing through routes with high moisture contents. This situation increases the corrosion risk in steel materials and reveals the necessity of evaluating the AC interaction together with the soil moisture content.

According to the signal/noise ratios, the greatest contribution to obtaining the lowest corrosion rate was made by bringing the cathodic protection level applied to the pipeline between -1300 mV and -1500 mV (SCE). These value ranges can be taken into account in determining the levels of cathodic protection used to reduce corrosion in natural gas pipeline operations.

With the linear regression equation which was derived from the linear regression model, it was possible to find the corrosion rates depending on the five studied factors. Although there are many factors that change the corrosion rate of the X 65 pipe in the soil, a close estimate of the corrosion rate in the pipes is made by evaluating the five most important factors identified through existing literature. By finding the corrosion rates with the help of the regression equation with high accuracy, the corrosion rates that may occur in the field conditions can be predicted during the pipeline planning stage and thus the selection or change of the pipeline route, the selection of the material wall thickness, and planning of pipeline control and maintenance process can be made in the most effective and efficient ways.

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