

Research Article

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Impact the sulphur content in Iraqi crude oil on the mechanical properties and corrosion behaviour of carbon steel in various types of API 5L pipelines and ASTM 106 grade B

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Abstract: Petroleum products are vital to the country's economy and are transported by pipelines. The main goal of this article is to investigate one of the components of crude oil, sulphur, and examine the impact on carbon steel pipes (API 5L [X60, X46, and X42] and A106 pipe) and demonstrate how sulphur content affects various types of API 5L XL independently from the other significant factors present in the crude oil. The sulphur has a huge impact on the mechanical characteristics and corrosion resistance of petroleum pipelines. We found that an increase in the sulphur content led to an increase in the corrosion rate (CR) and decreased the mechanical properties. It has been shown that the safest and most economical way to transport crude oil is through pipeline networks for gas and oil. Internal and external corrosions are the primary problems with API 5L and other steel pipelines used in the transportation of oil and gas. The TR-TXRF (X-ray Fluorescence Sulphur Tester) instrument is used in this study to determine the sulphur content of crude oil. Using weight loss and the Tafel extrapolation method, the CR, corrosion potential, and corrosion current of carbon steel pipes A106 and API 5L (X60, X46, and X42) in four immersion solutions were calculated. Using an optical microscope, scanning electron microscope, and energy dispersive spectroscopy (EDS), the products of corrosion were iron sulphate (Fe_2SO_4) and iron sulphide (FeS), and iron oxide (Fe_2O_3); the corrosion properties of the samples were measured morphologically. The results showed that the pipeline CR significantly increases with increasing concentration of

sulphur content. X60 pipe was more resistant to corrosion than X46 and X42 in API 5L-type pipes.

Keywords: sulphur content, corrosion behaviour, API 5L, A106 pipelines, weight loss, Tafel extrapolation

1 Introduction

The remains of ancient plants and animals that were buried in the primordial mud of lakes and swamps and sank to the ocean floor to form crude oil resulted in the formation of petroleum [1]. Physical properties of crude oils, such as API gravity, density, dynamic viscosity, and sulphur content, can be used to determine the market value of the oil [2]. Crude oil's appearance varies depending on its composition; samples can be yellow, red, or green, but the typical colour ranges from black to dark brown. Oil is made up of a variety of hydrocarbons, the most common of which are linear alkanes (paraffin), cycloalkanes (naphthenes), and aromatic hydrocarbons (arenes), as well as a proportion of complex asphalt compounds [3,4]. Crude oil is classified by its sulphur percentage (S%), which ranges from less than 0.1% to more than 5%. Crude oils with less than 1% sulphur are referred to as low-sulphur or sweet crude, while those with more than 1% sulphur are referred to as high-sulphur or sour crude. However, this ratio is not always consistent [5]. Some studies define sweet oil as having a sulphur value of 0.5%, while sour oil has more than 0.5% sulphur. environmental considerations require emissions from petroleum properties devised from these crude oils to contain limited levels of sulphur [6,7]. Pipelines transport petroleum products, including fossil fuels, gases, chemicals, and other hydrocarbon fluids. It has been demonstrated that oil and gas pipeline networks are the most cost-effective and safest means of transporting crude oils [8,9]. The main issues with pipelines used in oil and gas transportation are internal corrosion and external corrosion [10,11]. Internal corrosion

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is more problematic than external corrosion. This is because mitigation is difficult to maintain and inspect [12]. Understanding the crude oil composition and corrosion mechanism is a great way to predict the corrosion properties of pipeline surfaces [13,14]. It has been demonstrated that sulphur content in petroleum and its products is a significant factor in pipeline internal corrosion [15]. It is possible to assess the impact of sulphur on corrosion based on the type of crude oil. The degree of aggressiveness of the sulphur determines how quickly the pipeline wall corrodes. Sulphur poses serious risks to the security of crude oil transportation and poses difficulties for piping systems [16]. Carbon steel is used in industrial pipelines because it is widely available, durable, and has appropriate mechanical properties [17]. The primary objective of this study is to examine the effects of varying sulphur contents on the mechanical characteristics and corrosion resistance of API 5L (X42, X46, and X60) and A106 pipelines, whereby the mechanical characteristics and microstructures of the carbon steel pipes are analysed and contrasted. Weight loss is used to measure the rate of corrosion on carbon steel pipes, and the Tafel extrapolation technique is used to determine the polarization of samples impacted by a corrosive solution.

2 Experimental work

2.1 Specimen preparation

Samples of API 5L (X42, X46, and X60), as well as carbon steel A106, were contracted in collaboration with Basra Oil Company after chemical and tensile testing were performed to confirm pipe quality before proceeding with the remaining tests.

Chemical analysis was done according to ASTM 751-14, a standard [18] using a spectrum analyzer device (Model SPECTROTEST TXC25), as shown in Figure 1, to check its chemical composition for API 5L (X42, X46, and X60) and A106 pipes. The chemical composition differences between the actual test results and the standard values are explained by the standard ranges (max. or min. to max.) for all elements, and the tests obtained were within the ranges, as shown in Table 1.

The corrosion behaviour of pipeline steel was investigated using Tafel extrapolation and weight loss under various sulphur percentages in crude oil samples. The effect of sulphur percentages on pipeline steel corrosion was determined using immersion and electrochemical techniques.

Using wire-cut machining, 32 specimens were cut from the API 5L (X42, X46, and X60) and A106 pipes before the



Figure 1: Spectro mobile metal analysis.

experiment. Metallographic lapping machine by ASTM E3 standard [21] and several grades of emery paper (120, 200, 400, 600, 800, 1,000, 1,200, and 2,000) were used for surface grinding. Two divisions of the 32 specimens were created: 16 specimens for Tafel extrapolation and 16 specimens for weight loss. Afterward, all specimens were separated into eight groups (four for Tafel extrapolation and four for weight loss), with four specimens in each group based on the measurement techniques and immersion medium environments.

2.2 Analysis of sulphur content in crude oil

The TR-TCXRF (X-ray Fluorescence Sulphur Tester) device shown in Figure 2 was used to measure the percentage of sulphur content in the crude oil for the 12 samples from several Iraqi oil sites, as shown in Table 2. Four samples were selected from the twelve samples according to the difference in the percentage of sulphur in the crude oil. The four samples cover the range from min. to max. readings, as shown in Table 3.

2.3 Preparation of aggressive environments

Depending on the sulphur percentage in the crude oil for the four samples in Table 3, four solutions were prepared.

Table 1: Chemical composition of API 5L (X42, X46, and X60) and A106 pipes (wt%)

X42	C	Mn	P		S	V	Nb	Ti
	Max	Max	Min	Max	Max	Max	Max	Max
Standard [19]	0.28	1.3	—	0.03	0.03	≤0.15%	≤0.15%	≤0.15%
Actual	0.226	0.55	0.003		0.002	0.004	0.011	0.002
X46	C	Mn	P		S	V	Nb	Ti
	Max	Max	Min	Max	Max	Max	Max	Max
Standard [19]	0.28	1.4	—	0.03	0.03	≤0.15%	≤0.15%	≤0.15%
Actual	0.225	0.54	0.003		0.0069	0.004	0.011	0.002
X60	C	Mn	P		S	V	Nb	Ti
	Max	Max	Min	Max	Max	Max	Max	max
Standard [19]	0.28	1.4	—	0.03	0.03	≤0.15%	≤0.15%	≤0.15%
Actual	0.135	1.4	0.003		0.002	0.032	0.011	0.002
A106	C	Mn	P		S	V	Nb	Cr
	Max	Max	Min	Max	Max	Max	Max	Max
Standard [20]	0.3	1.06	—	0.035	0.035	0.08	0.15	0.4
Actual	0.281	0.43	0.003		0.002	0.004	0.011	0.055

**Figure 2:** TR-TCXRF (X-ray Fluorescence Sulphur Tester).

The samples were immersed for the weight loss and electrochemical corrosion tests. The concentration of sulphuric acid (H_2SO_4) was calculated, which was diluted with distilled water (4 l) depending on the sulphur percentage from Eq. (1) to obtain the four solutions. The four concentrations

Table 2: Sulphur content readings from 12 locations in Iraq

Sample No.	Location	Sulphur content (%)
1	Missan refinery	3.9436
2	Najaf refinery	3.9529
3	Nasiriya refinery	3.8839
4	Sayni refinery	3.411
5	Daura refinery	4.2533
6	Bazyan refinery	3.784
7	Baiji refinery	3.6844
8	Samaua refinery	4.4192
9	Kar refinery	3.644
10	Kassak refinery	3.8627
11	Basra refinery	3.0399
12	Cayara refinery	5.7855

of sulphur acid solution that was diluted (4 l) with distilled water are shown in Table 3, from the dilution Eq. (1):

$$C1 \times V1 = C2 \times V2, \quad (1)$$

Table 3: Four concentrations of sulphuric acid solution (immersion media)

Sample no.	Location	Sulphur content (%)	Sulphuric acid diluted in 4 l of distilled water (ml)
1	Cayara refinery	5.7855	0.3930 (S1)
2	Daura refinery	4.2533	0.2889 (S4)
3	Bazyan refinery	3.784	0.2570 (S3)
4	Basra refinery	3.0399	0.2065 (S2)

Table 4: CR and weight loss for API 5L (X42, X46, and X60) and A106 pipes

Pipes	Media	Weights (g)				ΔW (g)	CR (mm/year)	
		Original	After immersion					
			1 week	2 weeks	3 weeks			4 weeks
X60	S1	32.12	32.112	32.1035	32.093	32.0788	0.0409	0.0347
	S2	33.647	33.641	33.6328	33.624	33.6084	0.0386	0.0299
	S3	32.462	32.455	32.4474	32.437	32.4221	0.0402	0.0331
	S4	32.893	32.886	32.8781	32.867	32.8527	0.0406	0.0338
X46	S1	26.4119	26.405	26.3967	26.3877	26.3776	0.0343	0.0349
	S2	24.6096	24.604	24.5962	24.5876	24.5767	0.0329	0.0311
	S3	24.8714	24.866	24.8575	24.849	24.8381	0.0333	0.0319
	S4	25.356	25.35	25.342	25.3332	25.3223	0.0337	0.0324
X42	S1	23.9652	23.958	23.9505	23.9422	23.9281	0.0371	0.0356
	S2	24.8256	24.819	24.8114	24.8037	24.7921	0.0335	0.0327
	S3	24.2355	24.229	24.2211	24.2129	24.2015	0.034	0.0333
	S4	23.8797	23.872	23.8651	23.8569	23.8428	0.0369	0.0352
A106	S1	31.8299	31.822	31.8144	31.8065	31.7903	0.0396	0.0334
	S2	30.2991	30.292	30.2842	30.2775	30.2606	0.0385	0.0314
	S3	31.8061	31.798	31.7909	31.784	31.7672	0.0389	0.032
	S4	32.5281	32.52	32.5128	32.5049	32.4888	0.0393	0.033

where C_1 is the concentration of the concentrated solution, V_1 is the volume of the concentrated solution, C_2 is the concentration of the diluted solution, V_2 is the volume of the diluted solution, and S represents the solution.

H_2SO_4 (sulphuric acid) solution has a variety of effects, depending on its use and concentration. Its main impacts are as follows:

- Strong acids like sulphuric acid dissociate nearly entirely in water, releasing H^+ ions and sharply reducing the pH of the mixture.

Concentrated sulphuric acid is a potent oxidizer that can oxidize some organic and inorganic compounds. Low pH can produce extremely acidic conditions that affect chemical equilibrium, compound solubility, and

the behaviour of weak acids and bases in the solution. Because of these characteristics, it can influence reaction routes and results by taking part in the oxidation/reduction reactions, particularly at higher concentrations [22].

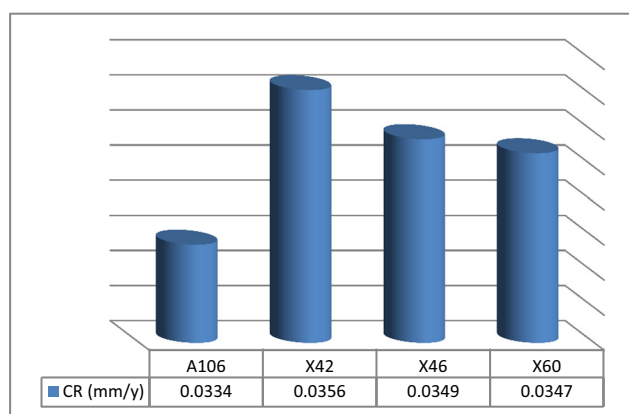
- Many metals, including iron, aluminium, and copper, as well as organic tissue, are severely corroded by sulphuric acid. This means that any items that come into contact with sulphuric acid in a lab or industrial setting need to be carefully chosen to resist corrosion; this frequently requires the use of specific coatings or materials that are resistant to acid.

3 Results and discussion

3.1 Corrosion rates (CRs)

3.1.1 Immersion test (weight loss)

The weight loss analysis is a popular, dependable, and efficient quantitative test technique for determining the rate of corrosion. It compares the sample weights before and after corrosion damage [23]. The experiments begin with the measurement of the original weight of the specimens. The specimens were then exposed to the four environments of sulphuric acid of different concentrations (ml) diluted in 4 l with distilled water ($S_1 = 0.3930$, $S_2 = 0.2065$, $S_3 = 0.2570$, and $S_4 = 0.2889$) for specific exposure times

**Figure 3:** CR in S1 medium for the four pipes.

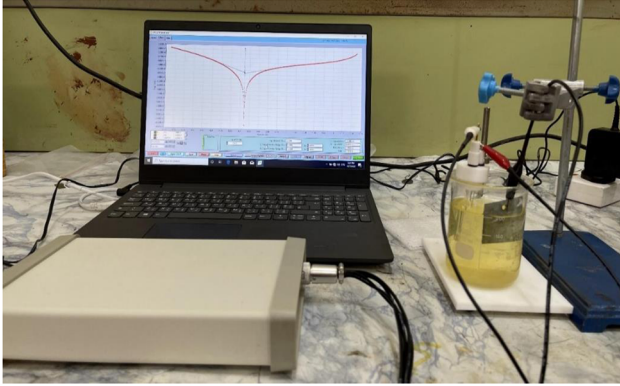


Figure 4: Assembled electrochemical corrosion test apparatus.

(7, 14, 21, and 28 days). After the first exposure period (7 days), the specimens were removed for cleaning, drying, and reweighing. The specimens were then returned to the second exposure period (14 days) and so on. The experiments were finished after the end of 28 days of immersion.

The specimens were cleaned in accordance with the ASTM G1-90 [24] standard and, when necessary, mechanically by carefully grinding with (1,200) grit emery paper, followed by rinsing with deionized water and drying under a hot air stream. All experiments were conducted at room temperature. The sample sizes for the mass loss experiment were cut into (20 mm × 20 mm × 11 mm) for API 5L X60 and A106 pipes and (20 mm × 20 mm × 8.5 mm) for API 5L (X46 and X42) pipes.

The corrosion behaviour was ascertained using formula (2), and the weight loss (in g) was computed as the difference in weight before and after the test [25]:

$$CR \text{ (mm/year)} = (K \times W) / (A \times T \times D), \quad (2)$$

where CR is the corrosion rate (in mm/year), K is a constant (8.76×10^4), T is the time of exposure (in h), A is the area (in cm^2), W is the mass loss (in g), and D is the density (in g/cm^3).

This part defines the mass difference caused by corrosive phenomena concerning the sample surface. The change in mass for all specimens subjected to corrosion testing is time-dependent. Mass loss weights increase in every environment as the specimen immersion time increases. One straightforward method for calculating CRs is the mass loss method. Weighing the intact sample material before and after the corrosion process (removing the corrosion product from the specimen after immersion) allowed us to compute the CR using Eq. (2). Table 6 shows the average CR and weight loss for API 5L (X42, X46, and X60) and A106 pipes.

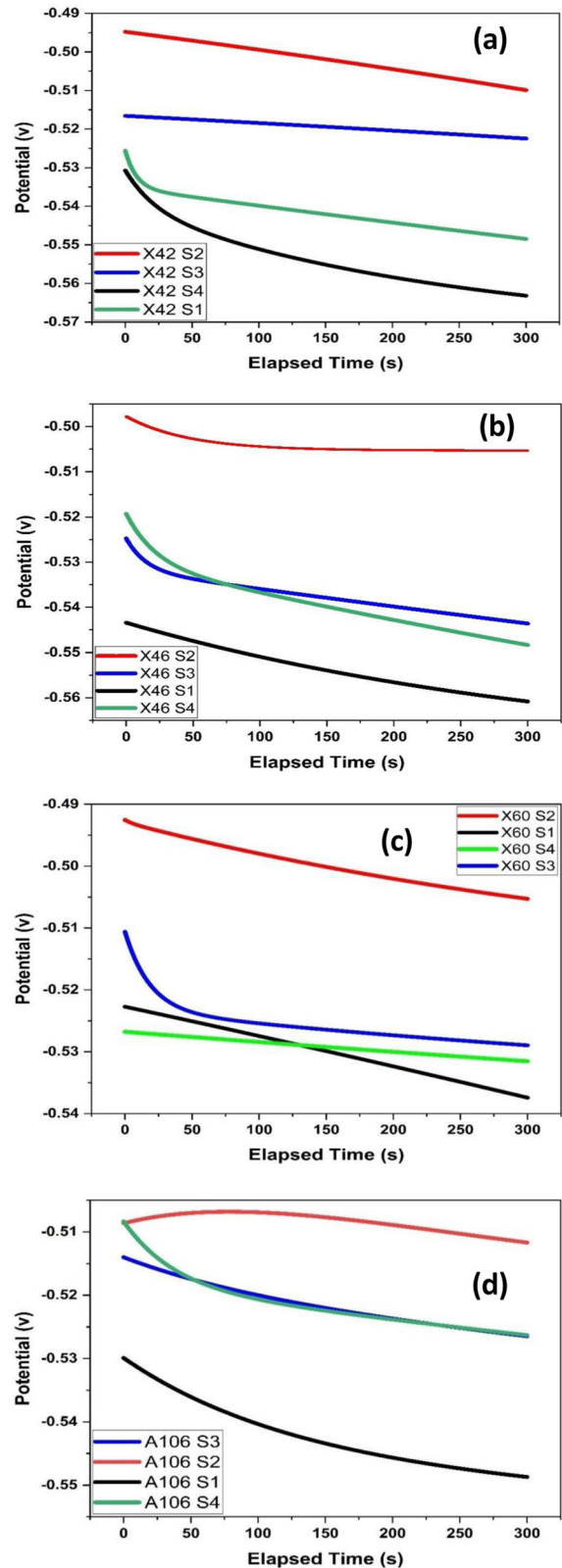


Figure 5: OCP variation vs elapsed time for four mediums with (a) X42 pipe, (b) X46 pipe, (c) X60 pipe, and (d) A106 pipe.

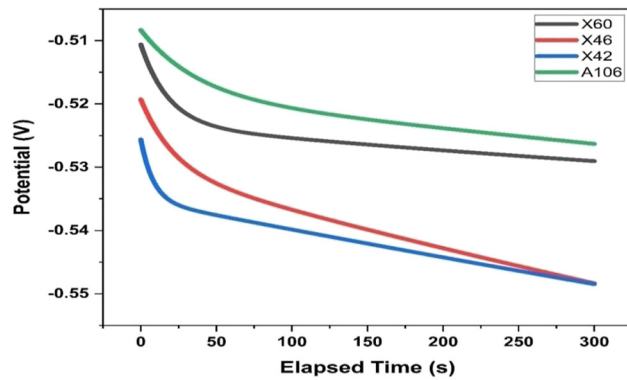


Figure 6: OCP test for potential with variation elapsed time for API 5L (X60, X46, and X42) and A106 pipes in immersion medium.

For the specimens used in Table 4, the weight losses for X60 in the S2 environment are the lowest value for CR compared to the other environments because the concentration of sulphur content was lower compared with other environments. The S3 environment is higher than S2, and S4 is higher than S3. The greatest are observed in the S1 environment (higher than S2, S3, and S4) with the increase

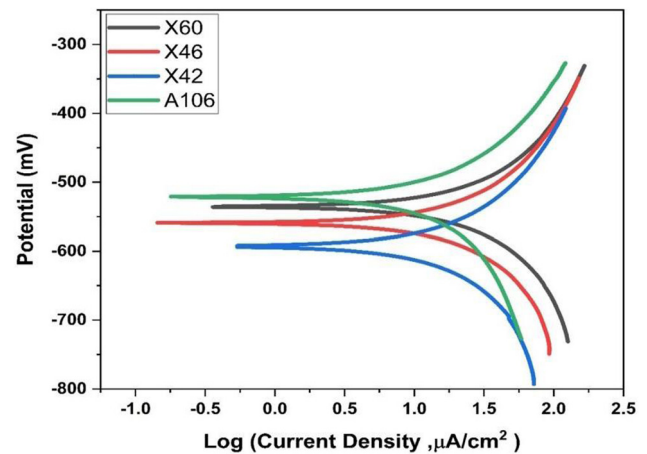


Figure 8: Tafel polarization for API 5L (X60, X46, and X42) and A106 pipes in immersion medium.

in the immersion time. The same applies to X46, X42, and A106 pipes.

All results are similar in Table 4 for the four pipes: the S2 environment had the least corrosion present, the S3

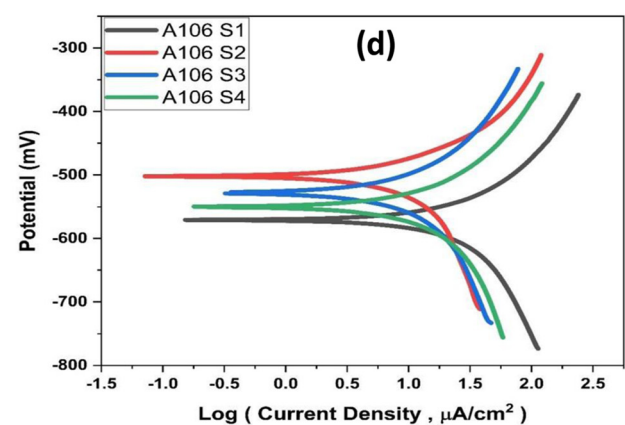
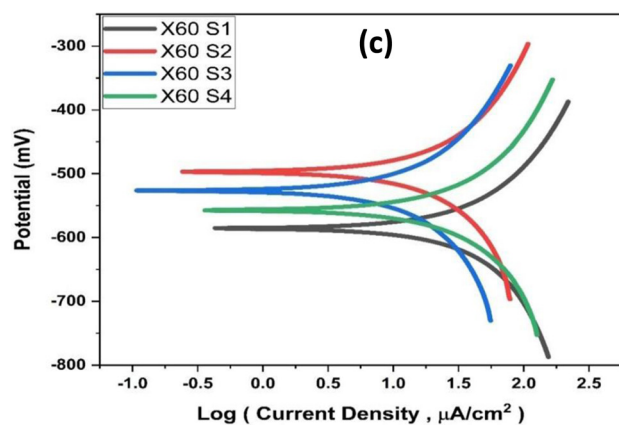
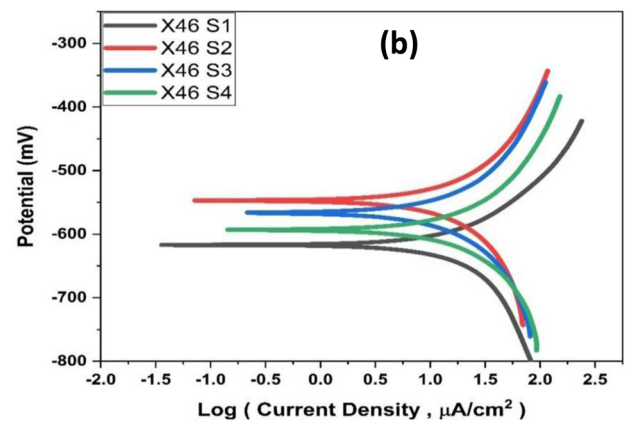
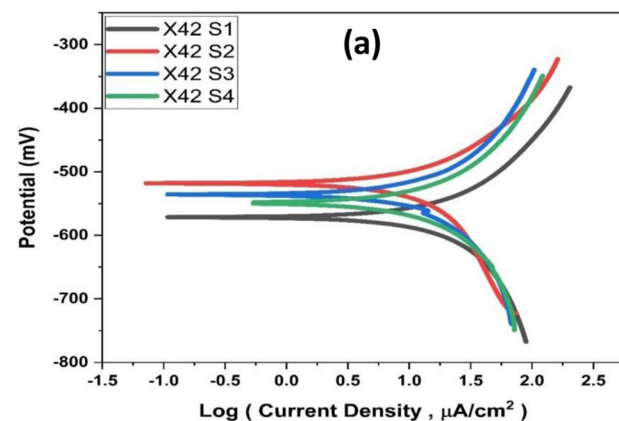


Figure 7: Tafel polarization for four media with (a) X42 pipe, (b) X46 pipe, (c) X60 pipe, and (d) A106 pipe.

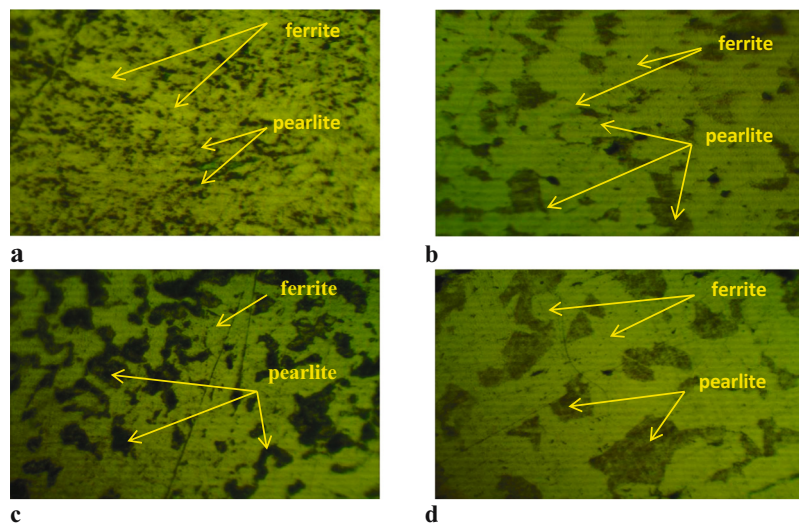


Figure 9: OM images for pipes (a) X60, (b) X46, (c) X42, and (d) A106 before corrosion.

environment had higher corrosion than S2, S4 had higher corrosion than S3, and the greatest corrosion was observed in the S1 environment because the concentration of sulphur content was higher compared with other environments.

The S1 medium was the highest carrier in which corrosion occurs, the API 5L X42 specimen in S1 exhibited higher CRs (0.0356 mm/year) than the API 5L X46 specimen in S1 (0.0349 mm/year), the API 5L X60 specimen in S1 (0.0347

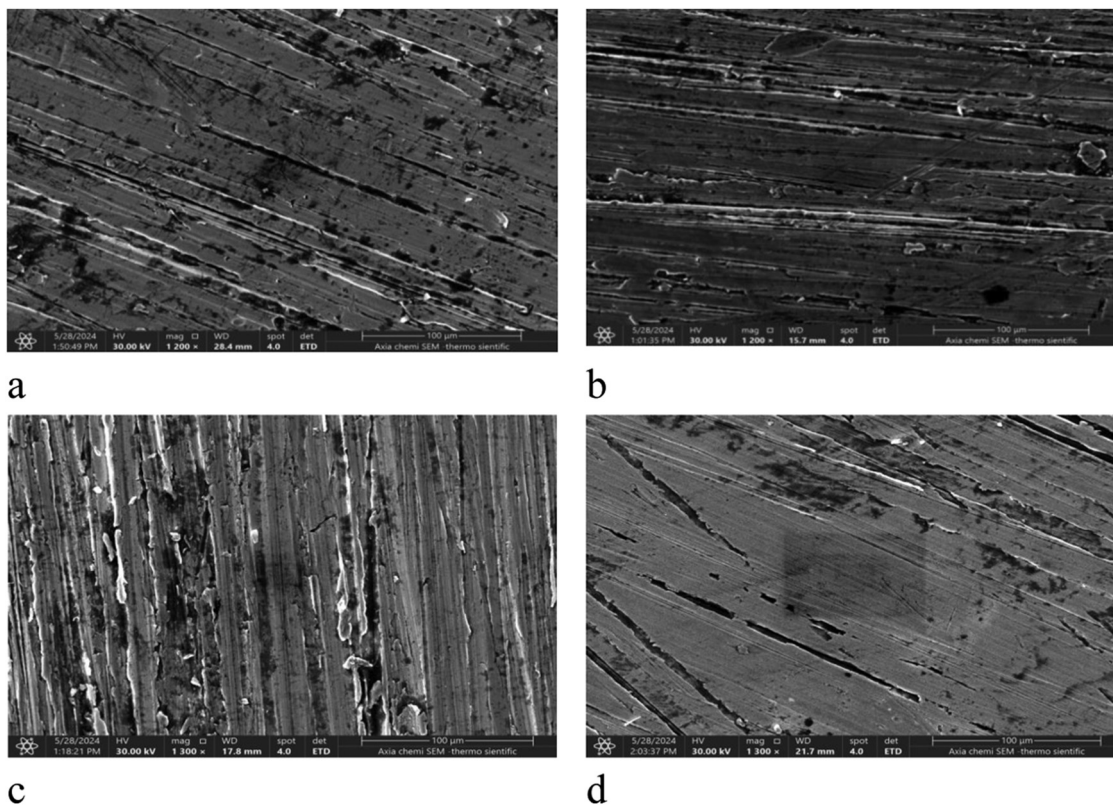


Figure 10: FE-SEM images for pipes (a) X60, (b) X46, (c) X42, and (d) A106 before corrosion. The presence of sulphur can decrease the corrosion resistance of API 5L steel.

mm/year), and the A106 specimen in S1 (0.0334 mm/year), as shown in Figure 3.

3.1.2 Electrochemical tests

The Tafel extrapolation method was used to detect corrosion by applying a slow linear potential and detecting the current response of the electrochemical cell, as shown in Figure 4 [26]. Electrochemical tests using the Tafel extrapolation method (linear potentiodynamic polarization tests

and open-circuit potential [OCP] measurements) were conducted to investigate the effects of S1, S2, S3, and S4 on the corrosion behaviour of API 5L (X42, X46, and X60) and A106 pipes. The tests were performed at room temperature following the guidelines of ASTM G5-87 [27] and ASTM G1-03 [28] in four environments using sulphuric acid of various concentrations (ml) diluted in 4 l of distilled water (S1 = 0.3930, S2 = 0.2065, S3 = 0.2570, and S4 = 0.2889). In these experiments, a potentiostat-type M Lab with a cell of three different electrodes (Ag/AgCl reference electrode, API 5L [X42, X46, and X60] and A106 pipeline steels as working

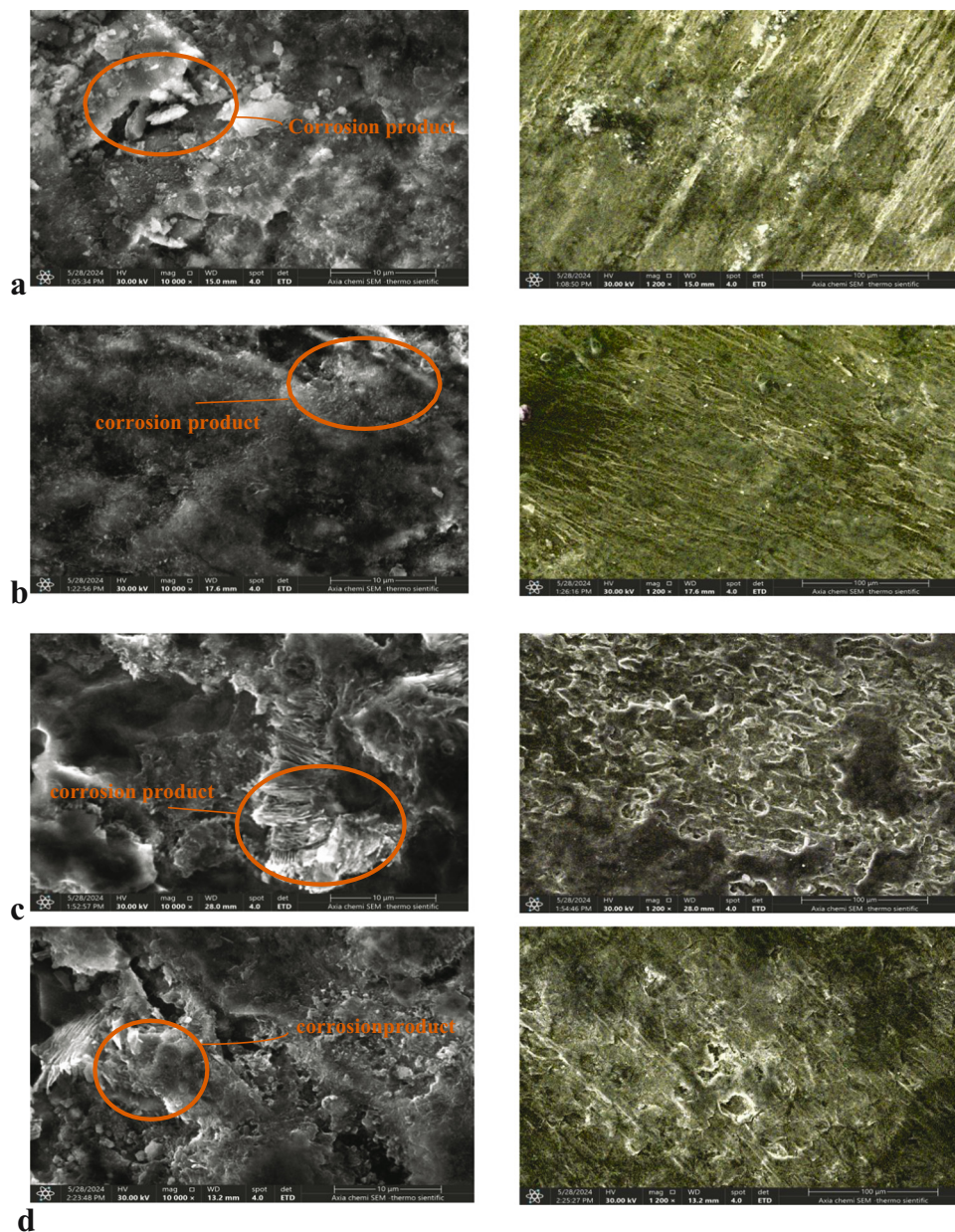


Figure 11: FE-SEM images for pipes (a) X60, (b) X46, (c) X42, and (d) A106 after corrosion.

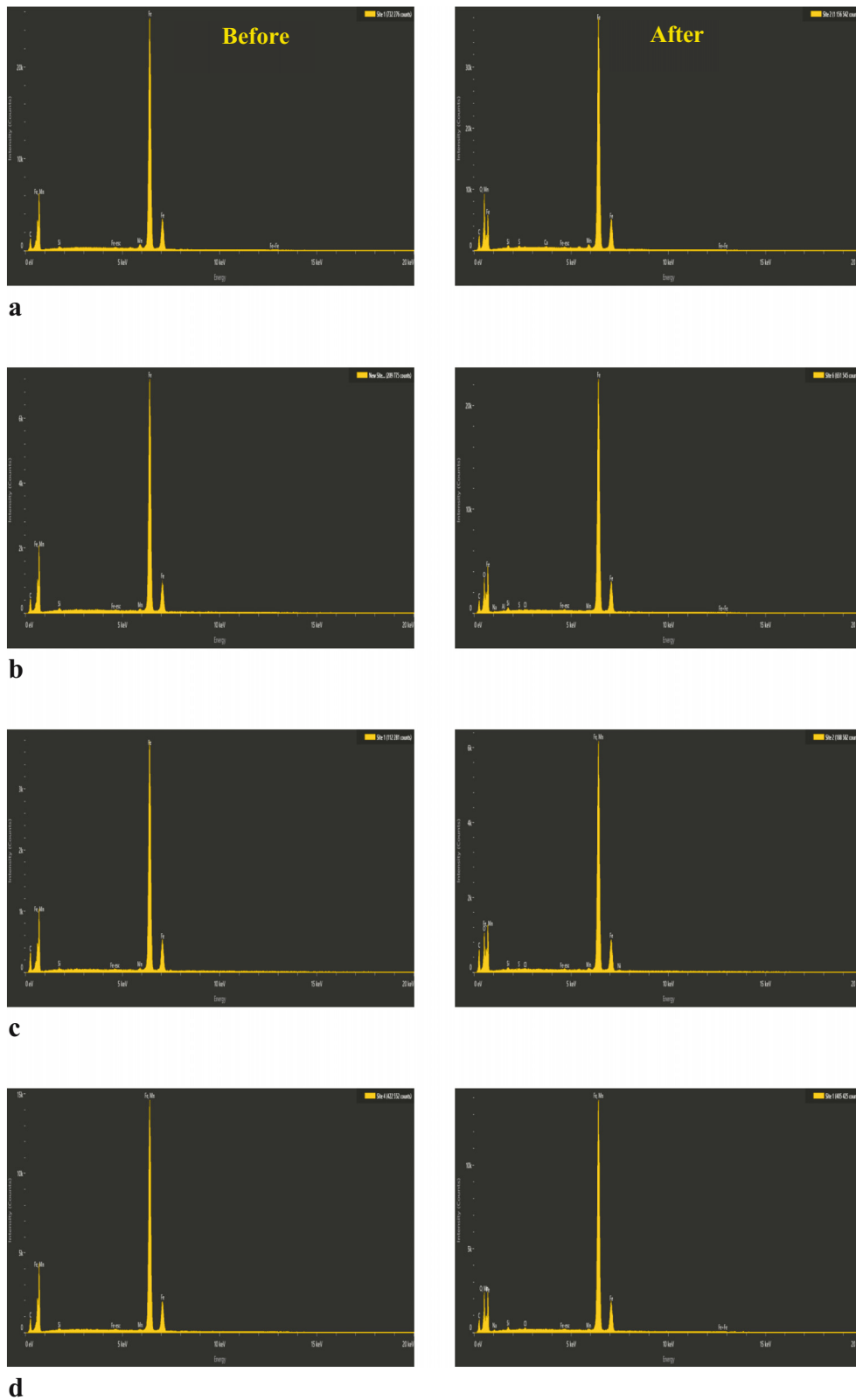
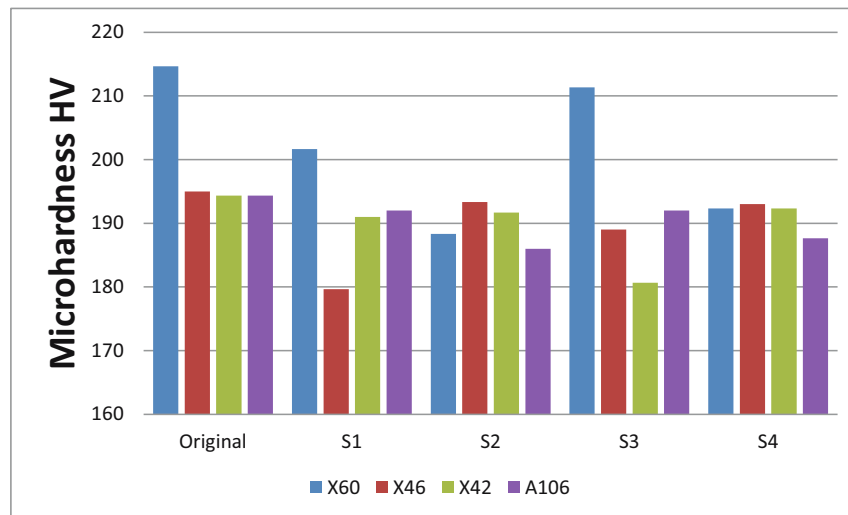


Figure 12: EDS images for pipes (a) X60, (b) X46, (c) X42, and (d) A106 before and after corrosion.

Table 5: Composition and product of the corrosion based on EDX analysis for API 5L (X60, X46, and X42) and A106 pipes

Pipe	Fe K		O K		S K		C K	
	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
X60	70.5	39.5	17.4	34.1	0.3	0.3	9.4	24.6
X46	72.8	42.2	17.2	34.7	0.3	0.3	7.9	21.2
X42	75.1	43.6	10.2	20.6	0.2	0.2	12.7	34.2
A106	75	44.3	13.5	27.9	0.1	0.1	9.2	25.3

**Figure 13:** Microhardness value changes for API 5L (X60, X46, and X42) and A106 pipes before (original) and after immersion.

electrodes, and a titanium auxiliary electrode) connected to a computer was used.

The testing began with a recording of OCP for up to 300 s of immersion time. The initial and final possible limits determine the scan's route. The polarization test was then performed with a consistent scan rate of 0.001 vs across all studies. Tafel lines were created using the M Lab software to extract anodic and cathodic slopes to measure E_{corr} , I_{corr} , and polarization resistance. The pipes API 5L (X42, X46, and X60) and A106 were divided into multiple identical coupons measuring 20 mm × 20 mm × 5 mm.

3.1.2.1 OCP

OCP is a function of time while submerged in varying concentrations of solutions and a material's susceptibility or ability to undergo electrochemical oxidation when subjected to a corrosive environment [29]. Using the Tafel extrapolation technique, the corrosion behaviour of pipes API 5L (X42, X46, and X60) and A106 was investigated in four solutions: S1, S2, S3, and S4 (as electrolytes). In general, the polarization curves varied across the four media, as shown in Figure 5a–d, where S1 was the most corrosive

medium, followed by S4 and S3, while S2 was the least corrosive medium, which shows that with increasing sulphur concentration, corrosion increases. The S1 medium had the highest sulphur content, and S2 had the lowest sulphur content.

An OCP diagram of four pipeline sheets of steel with immersion time depicted the sediment simulation liquid as well as anodic polarization for the media and pipeline sample reactions.

Table 6: Microhardness for API 5L (X60, X46, and X42) and A106 pipes before (original) and after immersion

Pipe	Average microhardness (HV)				
	Before immersion	After immersion			
		S1	S2	S3	S4
X60	214.66	201.66	188.33	211.33	192.33
X46	195	179.66	193.33	189	193
X42	194.33	191	191.66	180.66	192.33
A106	194.33	192	186	192	187.66

From the perspective of the material's thermodynamic corrosion, a negative potential increases the likelihood of corrosion. X42 was the most corrosion-prone, followed by X46 and X60, while A106 was the least likely to cause corrosion, as shown in Figure 6. The potential shifts towards increasingly negative values lead to an increase in the corrosion (*i.e.* decreased corrosion resistance).

3.1.2.2 Linear potentiodynamic polarization tests

The potentiodynamic polarization test is an electrochemical method that involves scanning the potential of the working electrode while measuring the corresponding current density. The dynamic potential polarization curve was analysed in order to examine the corrosion kinetics of four carbon steel pipes in sediment simulation fluid. Figure 7a–d depicts the polarization curve variation of the pipeline's potential in different environmental solutions: S1, S2, S3, and S4 (sediment simulation liquid). The polarization curve shows that the anode curves of the four pipeline steels are very smooth, with no passivation zone and an active dissolution process. The corrosion potential (E_{corr}) and corrosion current density (I_{corr}) are used to identify the metal's active degradability; the polarization test provides quantitative information about the corrosion resistance of the metal in a given environment. The polarization curves of all of the samples displayed a similar trend in behaviour, with only the change in I_{corr} and E_{corr} . Because the self-corrosion potential of a metal material can indicate the relative difficulty of losing electrons, it is generally the corrosion tendency of the metal material, with the more negative the self-corrosion potential, the greater the corrosion tendency [30]. X42 has the highest self-corrosion tendency and the lowest corrosion resistance compared to X46, X60, and A106, as shown in Figure 8.

3.2 Microstructure analysis

An optical microscope (OM) and scanning electron microscope (SEM) were used in microstructure analysis. The OM studies were carried out using an OM (Type GX41 OLYMPUS) in the college of Basra.

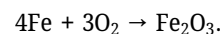
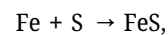
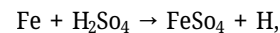
In contrast, the scanning electron microscopy investigations were carried out with an FE-SEM (INSPECT F-50) equipped with an energy dispersive spectroscopy (EDS) by ASTM E 1508-12a [31]. The tests were carried out in Baghdad by The Alkhora Company. The microstructures and the variation in the polished surface were shown in pipes API 5L (X60, X46, and X42) and A106 prior to the corrosion test using an OM shown in Figure 9 and by the FE-SEM test

shown in Figure 10. The microstructures observed by OM show the phases that are primarily ferrite with fine-grain pearlite for X60, ferrite grains, and pearlite colonies, which display the distinctive banded microstructure and form the microstructure of x46. Black flakes indicate that the specimen for X42 has pearlite banding in the structure, as well as visible ferrite grains containing pearlite. The A106 specimen shows fine grains of ferrite and pearlite. Ferrite (F) and a mass of carbide (Fe_3C) deposited in the grain boundary make up the majority of the carbon steel phase [32].

Sulphide inclusions can create anodic sites in the steel microstructure, making it more susceptible to localized corrosion, particularly pitting and stress corrosion cracking in environments containing chlorides or other aggressive ions. While sulphur in controlled amounts can improve machinability, excessive sulphur concentrations in API 5L steel typically lead to undesirable microstructural changes, such as the formation of MnS inclusions and grain boundary segregation. These changes negatively impact the material's toughness, ductility, and corrosion resistance, potentially compromising the steel's performance in demanding pipeline applications [33].

The analysis of the corrosion product's morphology after 28 days of immersion was performed. The micro-corrosion morphology of API 5L (X60, X46, and X42) and A106 are displayed in Figure 11, within the immersion media. The SEM image shows that all four pipeline steels have uniform corrosion characteristics and that the surface corrosion products of the four pipeline steels were separated into two layers. The top layer (10 μm) of the corrosion products was tough and unevenly distributed, while the bottom layer (100 μm) of corrosion products was dense and contained micro-cracks [34].

The EDS results of the samples (for four pipes) submerged in the four media (S1, S2, S3, and S4) for a period of 28 days compared with the samples before immersion are shown in Figure 12. The presence of sulphur and oxygen in the particles in the EDS results indicated that there may have been residues from iron oxide and aggressive media on the surface, as shown in Table 5.



3.3 Microhardness

The Vickers microhardness test was performed on 20 specimens (4 specimens as cast and 16 specimens from the

immersion test) and evaluated under ASTM E92-16 [35] at room temperature with a load of 500 g and a dwell time of 15 s. Three readings of each specimen were taken to obtain the mean value. The microhardness values were calculated directly for 16 specimens after a 28-day immersion test. The microhardness changes were caused by corrosion from immersion in four different media. As the corrosive medium changes from S1 to S4, the hardness values decrease, as shown in Table 6 and Figure 13.

4 Conclusion

Pipelines carry petroleum products, which are vital to the nation's economy. In this study, it was confirmed that the corrosion phenomenon in the pipeline increased due to increasing sulphur concentration in the crude oil transport. The CRs of pipes API 5L (X60, X46, and X42) and A106 were determined using weight loss and the Tafel extrapolation technique. The CR on the pipe surfaces increases with increasing H_2SO_4 concentration; the specimens in S1 (0.3930) had the highest CR, measured at 0.0356705 mm/y for X42.

The CRs of pipeline steels API 5L (X60, X46, and X42) and A106 in the four immersion solutions show a transition from high to low as immersion time increases, as proved by weight loss results. Iron sulphate (FeSO_4), iron sulphide (FeS), and iron oxide (Fe_2O_3) were the products of corrosion, according to the EDS results. The corrosion properties of the samples were assessed morphologically.

Future work will use other types of pipes (such as X80, X100, and X120) and other factors in crude oil such as salt and water as corrosive media.

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