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Comparison of Percentage Weight Loss and Corrosion Rate Trends in Different Metal Coupons from two Soil Environments

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Abstract Average percentage weight loss (APWL) and corrosion rate (CR) were determined for mild steel (MS), carbon steel (CS) and stainless steel (SS) strip coupons buried in a water-logged soil (WL) and a sandy soil (SD)for a period of 190 days. Post-exposure analyses of the coupons over the entire period showed that the APWL for the MS coupons retrieved from the water-logged soil and sandy soil sites were 5.4% and 2.8%, respectively. The corresponding CRs were 5.58 mpy and 3.18 mpy, respectively. Similarly, APWL for the CS coupons from the water-logged soil and sandy soil sites were 4.5% and 3.6%, respectively while their CRs were 3.51 mpy and 3.67 mpy, respectively. For the SS coupon, APWL and CR were 0.12% and 0.32 mpy, respectively from the water-logged soil and, 0.08% and 0.19 mpy, respectively for the sandy soil site. It was observed that generally, there was an inverse trend between weight loss and corrosion rates in the coupons as the exposure period increased such that, while APWL values were seen to be increasing, CR values were decreasing. This trend was observed in all three coupons and at both sites, except for a few excursions which did not significantly affect the established trend. It was observed that APWL increased by nearly the same ratio that CR decreased during the period of exposure of the coupons.

Keywords: *average percentage weight loss, corrosion rate, water-logged, sandy soil, mils per year*

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1. Introduction

When metals are exposed to the soil, they begin to corrode. The corrosiveness of soil can be defined as the capacity of producing and developing the corrosion phenomenon. Reference [1] defined soil-corrosion as the deterioration of metal or other materials brought about by chemical, mechanical and biological action by soil environment. One critical factor in soil corrosion is the moisture content of the soil. A general trend is that corrosion rates in soil increases with increased moisture content. Average and instantaneous corrosion rates in Q235 steel coupons buried in soils with different moisture content showed corrosion rate more in soil with 26% moisture than in soil with 12% moisture [2]. The duration of exposure of steel to corrosive soil environment is also a factor in the rate of corrosion noticed in the exposed steel.

With regards to biological activity and soil corrosion, reference [3] reported that incorporation of biocide in soil brought about a reduction in the numbers of bacteria present in the soil and subsequently, a reduction in the biocorrosion activity around and on steel coupons buried in the soil. The main types of bacteria associated with metals in terrestrial and aquatic habitats are sulfate reducing bacteria (SRB), sulfur-oxidizing bacteria, iron oxidizing/reducing bacteria, manganese-oxidizing bacteria, and bacteria secreting organic acids and slime [4]. Generally, buried steel pipelines and tanks suffer from soil corrosion because of one or more of the following conditions: high moisture content, a pH value less than 4.5, a resistivity less than 1000 Ωcm, presence of chlorides, sulphides and bacteria, and presence of stray currents [5].

The study of the soil as a corrosive environment is necessary due to the large number of buried pipelines and tanks, as their deterioration can appear to be a real economic and environmental problem through the years [6]. There is always a chance that pipelines could leak or rupture leading to hazardous failure which can inflict human fatality and also badly damage the environment and assets due to explosion and leakage [7,8,9].

One method of determining corrosion in metals is by weight loss analyses. Reference [10],in studying corrosion of stainless steel-304 in a brackish water environment, used weight loss analysis as well as open circuit polarization to determine corrosion in the steel. Similarly, reference [11], used average percent weight losses to determine corrosion of the coupons exposed to *Bacilluscereus*-SNB4 in wet and nutrient broth impregnated soils. They found that there were reductions in weights in the coupons after the observational period.

Corrosion reactions are electrochemical in nature and involve two types of reaction: anodic and cathodic. The anode is the part of the metal surface that corrodes - that is, the metal dissolves in the electrolyte. The anodic reaction for iron would be: $Fe \rightarrow Fe^{2+} + 2e^{-}$. This loss of electrons is called oxidation. The iron ion goes into solution and the two electrons are left behind in the metal. The cathode is that portion of the metal surface that does not dissolve. It is the site where chemical reactions absorb the electrons generated at the anode. The electrons generated as the iron dissolves at the anode travel through the metal to the cathodic surface area. There are two primary reactions possible at the cathode, the "hydrogen evolution reaction" and the "oxygen absorption reaction." Other reactions are possible but are encountered less often. In the hydrogen evolution reaction, the electrons combine on the surface of the metals with hydrogen ions in the electrolyte to form hydrogen molecules, which escape as gas bubbles. This consumption of electrons is called a reduction reaction and is as follows: $2H^{+} + 2e^{-} \rightarrow H_2$ [12].

Corrosion rate can be measured by gravimetric method. The simplest way of measuring the corrosion rate of a metal is to expose the sample to the test medium (e.g. sea water) and measure the loss of weight of the material as a function of time. Relative to metal density, exposed surface area, duration of exposure and some constant, the rate of corrosion of metal can be determined. Corrosion rate (CR), helps in understanding the vulnerability of metals to corrosion. Corrosion rate may be expressed in mils per year (mpy) of metals degraded. One (1) mil equals 0.001 inches. To give some perspective, most heat exchangers tubes are 0.10 inches thick so, a corrosion rate of 10 mpy will only take 10 years to penetrate the tube walls [13].

2. Materials and Methods

2.1. Site Selection

Two soil sites were selected for this study – a water-logged soil site and a sandy soil site. The water-logged site was in a swampy location and the soil was clay, characteristically wet, smooth, and greyish-black in colour and contained silt and other debris. The sandy soil was particulate and coarse, slightly moist and brownish in colour. Both soil sites are in the Niger Delta region of Nigeria. The study examines how these soil types affect metal corrosion. Comparing corrosivities of two soil types on three metallurgies under similar conditions provides some novelty to this research. During the study, the metal coupons were buried in the soils to a depth of 30 cm for a maximum 190 days.

2.2. Coupon Specimen and Preparation

Metal coupons of three metallurgies were used for the study. They are: mild steel (MS) coupons, carbon steel (CS) coupons and stainless steel (SS) coupons. All three coupon types were bar/strip style coupons. The MS coupons measured 4"x1" (100 mm x 25 mm) with a density of 7.85 gm/cm^3 and were manufactured by Visco Chemicals, Houston; the CS coupons measured 3"x½" x1/16" INSL, with a density of 7.85 gm/cm^3 from Rohrback Cosasco Systems, Aberdeen; while the SS coupons was 316-SS and measured 2-7/8"x7/8"x1/8", with a density of 7.98 gm/cm^3, also from Rohrback Cosasco Systems. There was no pre-treatment of the coupons before exposure to the soil sites as they were received in good condition and were in adequately sealed envelopes as delivered by the manufacturers. Before use, the coupons were carefully taken out from the sealed envelopes and buried in duplicates in the water-logged and sandy soil sites at a depth of 30 cm.

2.3. Weight Loss and Corrosion Rate Determination

The metal coupons were buried in the soil environments for a maximum of 190 days. On days 40 and 100, duplicate sets of the buried coupons were retrieved for analysis and the last set of coupons was retrieved on the last day of exposure (190 days). Interval monitoring of the buried coupons was to determine what corrosion effect had taken place on the coupons at the end of each observational period and to compare the effect of time on the rates of corrosion on the three coupon types in the two different soil environments under study. After retrieval from the soil sites (Figure 1.), the coupons were taken to the laboratory for cleaning and analyses to determine the weight loss and corrosion rates. Being in soil environments, the retrieved coupons did not have any oil residues on them but as expected, they were found to be covered with soil debris when they were recovered.

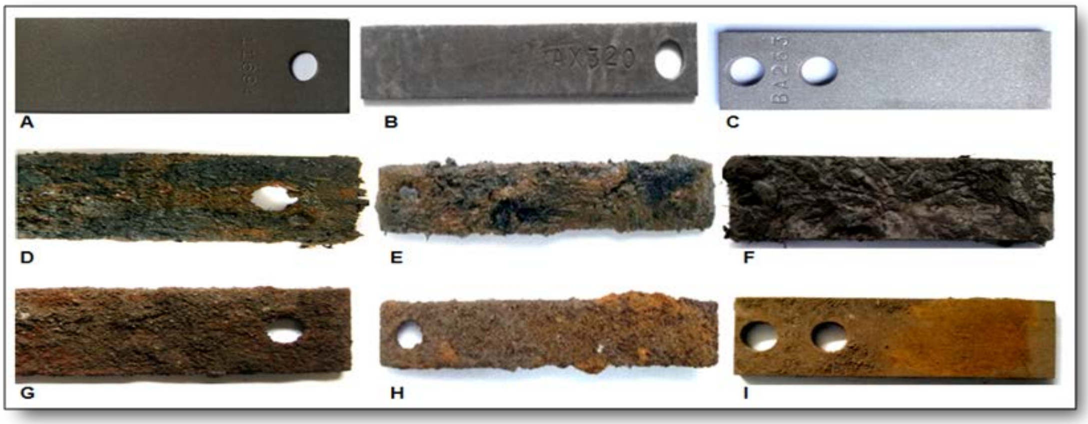

Figure 1. Coupons strips showing: Unexposed coupons, A – mild steel, B – carbon steel, C – stainless steel; Water-logged soil retrieved coupons, D – mild steel, E – carbon steel, F – stainless steel; and Sandy soil retrieved coupons, G – mild steel, H – carbon steel, I.

In the laboratory, outer soil debris on the coupons was carefully removed. They were then cleaned with inhibited acid (15% HCl) to remove corrosion products on the surface of the coupons according to ASTM G1 (Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens). The coupons were then rinsed under running water. Next, the coupons were placed in an oven at 70°C for 15 minutes to dry them. After drying, they were placed in a desiccator to cool after which they were weighed to a constant weight using a Mettle Toledo weighing balance (New Classic ML 204, Switzerland). The weight of the retrieved coupons before cleaning was compared to the initial weight, the difference indicating the metal loss during the exposure period. The corresponding average percentage weight loss (APWL) and corrosion rate (CR) were calculated.

Corrosion rate was calculated assuming uniform corrosion over the entire surface of the coupons. The corrosion rate in mils per year (mpy) was calculated from the weight loss using the formula:

$$CR = \frac{W}{(D \times A \times t)} \times k$$

where:

W = weight loss in grams
k = constant (22,300)
D = metal density in g/cm^3
A = coupon area (inch^2)
t = time (days)

3. Results and Discussion

Upon retrieval of the coupons after each burial period of 40, 100 and 190 days, the coupons were cleaned and analyzed to determine the metal loss and subsequently, the corrosion rate. Data on the weights of duplicate sets of all the coupons before and after analysis are shown on Tables 1 and 2 for the water-logged soil and sandy soil, respectively. The average percentage weight loss and corrosion rate data are shown on Tables 3 and 4, respectively.

The results showed that generally, weight loss increased over time while corrosion rate decreased. Reference [14] found that average corrosion rate decreased with exposure time. In a another study, polarization resistant (PR) measurement of corrosion rates found that the PR technique overestimated corrosion rates but predicted a decrease in corrosion rate over time [15]. These studies confirm our findings about corrosion rates in the steel coupons in this study.

Table 1. Weight of duplicate coupons from the water-logged site

	40 days			100 days			190 days		
Coupon type	Initial	Final	Weight loss	Initial	Final	Weight loss	Initial	Final	Weight loss
Mild steel	29.780	28.927	0.853	29.810	27.795	2.015	30.482	27.249	3.233
	30.345	29.809	0.536	29.690	28.457	1.233	30.036	28.118	1.918
Carbon steel	17.186	17.073	0.113	11.109	10.668	0.441	11.214	9.593	1.621
	17.200	17.062	0.138	17.223	16.712	0.511	17.178	16.129	1.049
Stainless steel	37.106	37.063	0.043	37.112	37.075	0.037	37.124	37.081	0.043
	37.007	36.961	0.046	37.141	37.097	0.044	37.082	37.030	0.051

Table 2. Weight of duplicate coupons from the sandy soil site

	40 days			100 days			190 days		
Coupon type	Initial	Final	Weight loss	Initial	Final	Weight loss	Initial	Final	Weight loss
Mild steel	29.982	29.501	0.481	28.852	28.365	0.487	30.004	28.151	1.853
	29.983	29.526	0.457	31.881	31.150	0.731	31.038	29.961	1.077
Carbon steel	11.185	10.898	0.287	11.151	10.534	0.618	11.120	10.388	0.732
	17.153	16.973	0.180	17.185	16.708	0.477	17.228	16.478	0.750
Stainless steel	36.634	36.612	0.022	37.022	37.013	0.008	36.816	36.766	0.050
	37.133	37.101	0.032	36.565	36.549	0.015	37.104	37.054	0.049

Table 3. Average percentage weight loss in coupons after 40, 100 and 190 days

	Mild steel coupon			Carbon steel coupon			Stainless steel coupon		
Days	40	100	190	40	100	190	40	100	190
Water-logged-soil	2.3%	5.5%	8.5%	0.7%	3.3%	9.4%	0.12%	0.11%	0.13%
Sandy-soli	1.6%	2.0%	4.8%	1.6%	3.9%	5.2%	0.07%	0.03%	0.14%

Table 4. Average corrosion rates (mpy) in coupons after 40, 100 and 190 days

	Mild steel coupon			Carbon steel coupon			Stainless steel coupon		
Days	40	100	190	40	100	190	40	100	190
Water-logged-soil	6.2	5.8	4.8	1.91	3.4	5.3	0.60	0.22	0.13
Sandy-soli	3.9	3.0	2.6	4.4	3.8	2.8	0.36	0.06	0.14

3.1. Average Percentage Weight Loss (APWL) and Corrosion Rates

3.1.1. Mild Steel in Water-logged Soil and Sandy soil

After the observational periods of 40, 100 and 190 days, APWLs in the MS coupons from the waterlogged site were 2.3%, 5.5% and 8.5%, respectively, representing an overall average of 5.4%.(Figure 2).In the sandy soil site, the APWLs were 1.6%, 2.0%, and 4.8%, respectively (overall average of 2.8%).At both sites, there was increase in weight loss with respect to days of exposure.

Corrosion rates for the MS coupons from the water-logged site after 40, 100 and 190 days were 6.16 mpy, 5.77 mpy and 4.81 mpy, respectively, giving a composite average of 5.58 mpy. In the sandy soil, the CRs were 3.92 mpy, 3.04 mpy and 2.58 mpy (average, 3.18 mpy), respectively. (Figure 3). Here, we see a reversed trend – decrease in the CRs – at both sites, with respect to days of exposure.

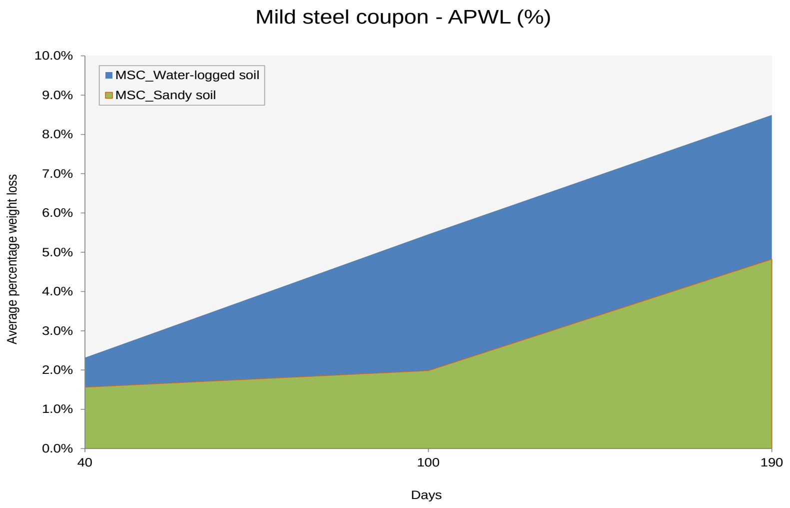

Figure 2. Average percentage weight loss in mild steel coupons from water-logged and sandy soil sites

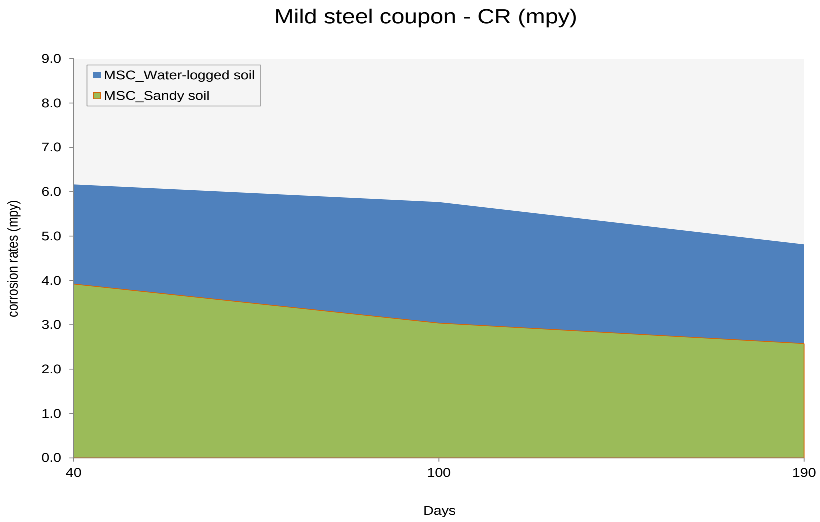

Figure 3. Corrosion rates in mild steel coupons from water-logged and sandy soil sites

3.1.2. Carbon Steel in Water-logged Soil and Sandy Soil

APWLsin the CS coupons from the water-logged soil after 40, 100 and 190 days were 0.7%, 3.3% and 9.4%, respectively (combined average, 4.5%), while in the sandy soil the APWLs were 1.6%, 3.9% and 5.2%, respectively (combined average, 3.6%). Again, we observe an increasing trend in APWL over time, at both sites (Figure 4).

For the CS coupons, CRs were 1.91 mpy, 3.36 mpy and 5.25 mpy from the water-logged soil after 40, 100 and 190 days, respectively (average of 3.51 mpy), while the CRs from the sandy soil site were 4.37 mpy, 3.83 mpy and 2.82 mpy, respectively (average 3.67 mpy). Here we see the decreasing CR trend only consistent in the sandy soil samples but not in the water-logged sample. This may be taken as an exception from the expected trend (Figure 5).

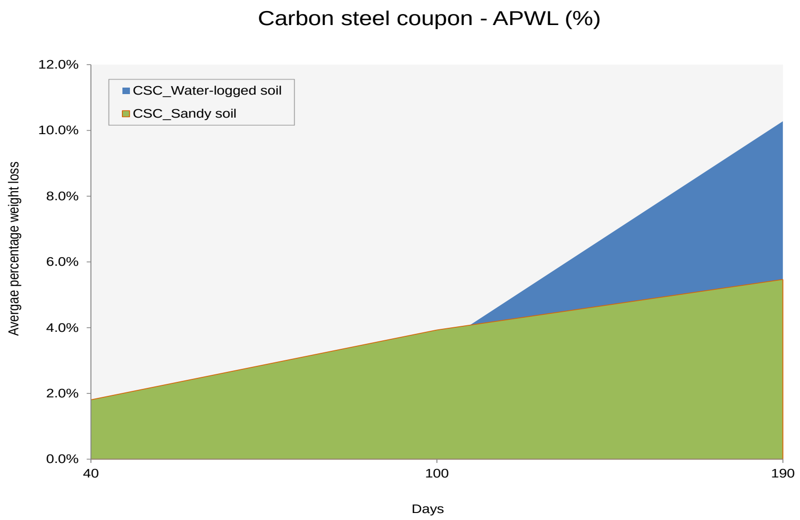

Figure 4. Average percentage weight loss in carbon steel coupons from water-logged and sandy soil sites

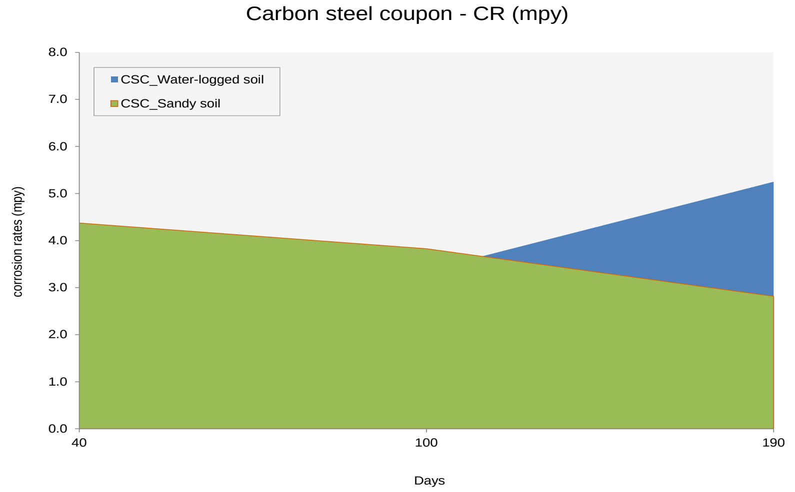

Figure 5. Corrosion rates in carbon steel coupons from water-logged and sandy soil sites

3.1.3. Stainless Steel in Water-logged Soil and Sandy Soil

In the water-logged site, APWLs for the SS coupons were 0.12%, 0.11% and 0.13% after 40, 100 and 190 days respectively, (combined average of 0.12%), while the APWLs in the sandy soil were 0.07%, 0.03% and 0.14%, respectively, for a combined average of 0.08%. Here, we see a near-similar increasing pattern as noted earlier, except for the dips on day 100 at both sites (Figure 6).

Corrosion rates for the SS coupons from the water-logged soil site were 0.60 mpy, 0.22 mpy and 0.13 mpy after 40, 100 and 190 days, giving a cumulative average of 0.32 mpy. For the sandy soil site, the corrosion rates were 0.36 mpy, 0.06 mpy and 0.14 mpy, respectively, for a cumulative average of 0.19 mpy. Expectedly, here we see the decreasing pattern of CR with respect to exposure days, with only an exception in the sandy soil on day 190 (Figure 7).

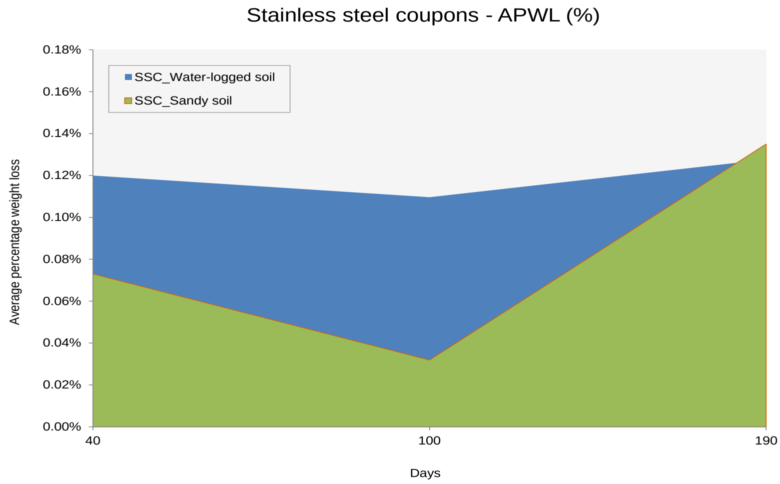

Figure 6. Average percentage weight loss in stainless steel coupons from water-logged and sandy soil sites

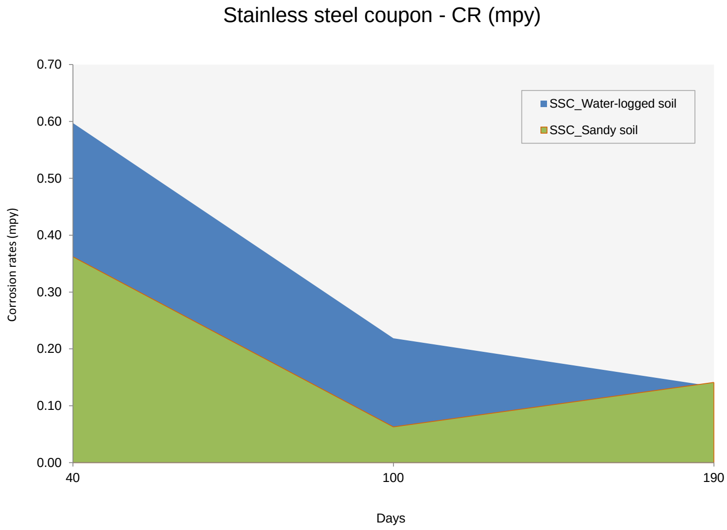

Figure 7. Corrosion rates in stainless steel coupons from water-logged and sandy soil sites

These results showed a general pattern of increase in average percentage weight loss (APWL) and a corresponding decrease in corrosion rate (CR) in the coupons, with respect to time. An inverse proportional trend seems to exist between the weight loss and corrosion rate over time. This inverse trend between APWL and CR was very clear and sharp for the MS coupons (Figure 2 and Figure 3); for the CS coupons(Figure 4 and Figure 5), except for the water-logged site; and also for the SS coupons (Figure 6 and Figure 7), except for a one-point excursion on day 100 for APWL and day 190 for CR.

Comparatively, weight loss and corrosion rates were more in the water-logged soil than in the sandy soil site. This may be attributed to the higher moisture content in the former. The water-logged soil had a moisture content of 104% while the sandy soil had just 20% moisture. According to reference [16], the corrosivity of soils towards mild steel, in general, has been found to be at maximum at 65% moisture content of their water holding capacity, which may be termed as "Critical Soil Moisture Content." Corrosion of mild steel in a soil becomes appreciable only when the soil moisture content ≥ 50% of its water holding capacity. In one study, reference [17] found that soil A with higher moisture content (18.46%) accelerated the corrosion process of buried coupons more than soil B with 17.00% moisture content.

Comparing the APWL and CR trends in the MS and CS coupons showed that it was a near 1:1 ratio between increase in APWL and decrease in CR. This means that CR decreased in the MS and CS coupons by nearly the same margin of the corresponding APWL increases. Reference [18] found that the percentage of weight loss of mild steel in seawater increased as immersion period increased. Investigating further, they established that corrosion current density (i_{corr}), which increased at early immersion period, decreased as immersion period increased. In a study to compare corrosion rates based on various electrode probe systems, reference [19], noted that corrosion rates measured by four different electrode systems show that the corrosion rates follow the order: linear polarization resistance>weak polarization> electrochemical impedance spectroscopy>coupon. They reported that the rates showed a consistent variation in trend when compared with the weight-loss coupon and show that the corrosion rate decreases with the immersion time. Some researchers have reported corrosion rates by electrochemical methods being close to weight loss measurements in water samples. Reference [20] reported corrosion rate calculated by means of electrochemical methods is close to but slightly higher than when it is calculated by loss in weight. They found that corrosion rate of low carbon steel is nearly four times higher in the 3.5% NaCl solution than in the natural seawater.

This similarity in APWL/CR trends in the MS and CS coupons may have to do with the compositional similarity in their alloys. Mild steel and carbon steel are close alloys, differing only slightly in their carbon contents. Mild steels (low-carbon steels) have less than 0.30 percent carbon and are the most commonly used grades. They machine and weld nicely and are more ductile than higher-carbon steels. Carbon steel (medium-carbon steels) has from 0.30 to 0.45 percent carbon. Increased carbon means increased hardness and tensile strength, decreased ductility, and more difficult machining [21]. The close carbon content of these steel types probably explains why the APWL and CR values were close.

For the SS coupons, this APWL/CR inverse trend was also noticed. For APWL, there was a general increasing pattern except for a dip on day 100. For CR, a decreasing pattern was noticed with an exception spike on day 190. However, these excursions do not eclipse the general APWL-increase/ CR-decrease pattern that were observed.

4. Conclusion

As steel undergoes corrosion in a soil environment, there tends to be an inverse relationship in the weight loss and corrosion rate trends in the exposed steel. While weight loss tends to increase over time, the highest being at the time that the corrosion process is initiated, corrosion rate tends to decrease simultaneously.

Appreciation

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References

[1] Chaker, V. and Palmer, J. D., ASTM Committee G-1 on Corrosion of Metals. "Effect of Soil Characteristics on Corrosion", ASTM International, pp: 81. 1989.

[2] Wan, Y., Ding, L., Wang, X., Li, Y., Sun, H. and Wang, Q., "Corrosion Behaviors of Q235 Steel in Indoor Soil", International Journal of Electrochemical Science, 8: 12531-12542. 2013.

[3] Oparaodu, K.O., and Okpokwasili, G.C., "Effect of Tetrakis (Hydroxymethyl) Phosphonium Sulphate Biocide on Metal Loss in Mild Steel Coupons Buried in a Water-logged Soil." *Journal of Applied & Environmental Microbiology*, 2 (5): 253-256. http://pubs.sciepub.com/jaem/2/5/9. 2014

[4] Beech, I.B. and Coutinho, C.L.M., "Biofilms on corroding materials". In: *Biofilms in Medicine, Industry and Environmental Biotechnology - Characteristics, Analysis and Control*, Edited by Lens, P., Moran, A.P., Mahony, T., Stoodly, P., and O'Flaherty, V., IWA Publishing of Alliance House, 115-131. 2003.

[5] Cunat, P., "*Corrosion Resistance of Stainless Steels in Soils and in Concrete"*. Paper presented at the Plenary Days of the Committee on the Study of Pipe Corrosion and Protection, Ceocor, Biarritz. 2001.

[6] Ferreira, C.A.M., Ponciano, J.A.C., Vaitsman, D.S. and Pérez, D.V., "Evaluation of the Corrosivity of the Soil through Its Chemical Composition". *Science of the Total Environment*, 388: 250-255. 2007.

[7] Hopkins, P., "Transmission Pipelines: How to Improve Their Integrity and Prevent Failures" In: Denys, R. (ed). *Pipeline Technology*. In the Proceedings of the 2nd *International Pipeline Technology Conference*, (PTC'96), Amsterdam, pp: 683-706. 1995.

[8] National Energy Board, "Stress Corrosion Cracking on Canadian Oil and Gas Pipelines", Report of the enquiry. Calgary. MH-2-95. 1996.

[9] Yahaya, N., Noor, N.M., Din, M.M., and Nor, S.H.M., "Prediction of CO2 Corrosion Growth in Submarine Pipelines". *Malaysia Journal Civil Engineering*, 21 (1): 69-81. 2009.

[10] Kumar, R.K.S., Vijian, P., Solomon, J.S. and Berchmans, L.J., "Corrosion Studies on Stainless Steel-304 in BrackishEnvironment."*International Journal of Emerging Technology and Advanced Engineering*, 2 (5): 178-182. 2012. http://www.ijetae.com/files/Volume2Issue5/IJETAE_0512_29.pdf

[11] Bano, A. S. and Qazi, J. I., "Soil Buried Mild Steel Corrosion by Bacillus cereus-SNB4 and its Inhibition by Bacillus thuringiensis-SN8.", *Pakistan Journal of Zoology*. 43 (3): 555-562. 2011.

[12] Nalco Company, "Corrosion", *Oil Field Chemicals Training Manual*. CAPEX College, Nalco Energy Services, Sugar Land, Texas. 2004.

[13] Uy, M.C., "Corrosion Coupons. Technical Publication", WET, USA Inc., Illinois. 1994.

[14] Wan, Y., Ding, L., Wang, X., Li, Y., Sun, H. and Wang, Q., "Corrosion Behaviors of Q235 Steel in Indoor Soil", *International Journal of Electrochemical Science*, 8: 12531-12542. 2013.

[15] Beavers, J.A., and Durr, C.L, "*Corrosion of Steel Piling in Nonmarine Applications*", NCHRP Report Issue 408, Transportation Research Board, National Research Council, Washington DC., p. 17. 1998.

[16] Technical Manual: "Electrical Design, Cathodic Protection", Headquaters Department of theArmy, Washington, D.C. 22: No. 5-811-7, pp 13. 1985.

[17] Adeosun, S.O., Sanni, O.S., Agunsoye, J.O., Lawal, J.T. and Ayoola, W.A., "Corrosion Responses of Welded Mild Steel Embedded in Coastal Soil Environment", International Conference on Innovations in Engineering and Technology (IET 2011), August 8th-10th. 2011.

[18] Wan Nik, W.B, Zulkifli, F., Rahman, M.M., and Rosliza, R., "Corrosion Behavior of Mild Steel in Seawater from Two Different Sites of Kuala Terengganu Coastal Area", *International Journal of Basic & Applied Sciences*, 11: 75-80.2011.

[19] Wu., J.W., Bai, D., Baker, A.P., Li, Z.-H. and Liu, X.-B., "Electrochemical techniques correlation study of on-line corrosion monitoring probes", http://onlinelibrary.wiley.com/doi/10.1002/maco.201307175/pdf . 2013.

[20] Möller, H., Boshoff, E.T.and Froneman,H., "The corrosion behaviour of a lowcarbon steel in natural and synthetic seawaters" *The Journal of The South African Institute of Mining and Metallurgy* 106:85-592. 2006.

[21] Capudean, B., "Carbon content, steel classifications and alloy steels", *Practical Welding Today®*. 2003. http://www.thefabricator.com/article/metalsmaterials/carbon-content-steel-classifications-and-alloy-steels