

Comparison of Trends in Corrosion Rates of Various Metal Coupons in Soil Environment

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ABSTRACT

The study aims to determine corrosion rates (CR) for mild steel (MS), stainless steel (SS304), and aluminium (Al) strip coupons buried in soil samples for various time durations using the weight loss method. Post-exposure analyses of corrosion coupons from all the periods showed that the highest CR for MS coupon retrieved from the soil sample was 159.20 mg dm⁻² day⁻¹. The lowest CR was observed in SS304 with 0.11 mg dm⁻² day⁻¹. The average CR for 6 hr in MS was 77.22, in SS304 is 5.065 and in Al was 13.26. For the highest time duration (96 h), CR in MS was 2.82, in SS304, it was 0.207, and in Al, it was 0.57 mg dm⁻² day⁻¹. Overall highest CR was observed in all samples of MS and the lowest CR was observed in SS304. It was observed that there was an inverse trend between weight loss and CR in the metal coupons and as the exposure period increased, CR values were decreased. This trend was observed in all three coupons and in all conditions, except for a few excursions which did not significantly affect the established trend.

Key words: Corrosion, Soil corrosion, Corrosion rate, Metal corrosion, Weightloss method

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 the soil environment. One critical factor in soil corrosion is the moisture content of the soil. The effect of soil and its mechanical properties on the steel metal plates is studied using weight loss methods. It is observed that the intensity of attack and corrosion rate (CR) are dependent on soil texture and content of moisture in it. CR is higher in clayey soil than in mixed and sandy soils. It is observed from the study that mild steel (MS) undergoes only less violent surface-level corrosion in the studied duration when buried underground.

Soil is one of the most corrosive medium found in the world, but it is very difficult to study its nature of its corrosivity due to its diversification. Corrosion is one of the most challenging problems in many industries as well as in construction and infrastructure industries where metals are directly gets in contact to various soil environments throughout their designed life. Several studies on corrosion in soil [2-8] have given useful information on soil's overall properties and physicochemical properties such as chloride ions, sulfate ions and organic matter, and conductivity, which influence the rate of the corrosion of the soil, making corrosion a rapid and firm process [9-13].

A general trend is that CR in soil increase with increased moisture content. Average and instantaneous CR in Q235 steel coupons buried in soils with different moisture content showed CR more in soil with 26% moisture than in soil with 12% moisture [14]. The duration of exposure of steel to a 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 [15] reported that

the 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, sulfur-oxidizing bacteria, iron oxidizing/reducing bacteria, manganese oxidizing bacteria, and bacteria secreting organic acids and slime [16]. In general, buried steel pipelines and tanks suffer from soil corrosion due to one or more of the following conditions: High moisture content, a pH value <4.5, a resistivity < 1000 Ω cm, presence of chlorides, sulfides and bacteria, and presence of stray currents [17].

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 [11]. 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 [18-20]. One method of determining corrosion in metals is by weight loss analyses. Reference [21], in studying corrosion of stainless steel-304 (SS) in a brackish water environment, used weight loss analysis as well as open circuit polarization to determine corrosion in the steel. Similarly, reference [22], used average percent weight

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losses to determine corrosion of the coupons buried in soil samples. 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: $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$. 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: $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ [23].

CR can be measured by gravimetric method. The simplest way of measuring the CR of a metal is to expose the sample to the test medium 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. CR helps in understanding the vulnerability of metals to corrosion. CR 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 CR of 10 mpy will only take 10 years to penetrate the tube walls [24].

In agriculture sector corrosion, the first year of exposure, the CR values for 63% saturated ammonium nitrate solution are all around 250 mm for galvanized steel and 1,250 mm for MS. As long as, proper surface cleaning, preparation, and coating are done, carbon steel is a low-cost alternative for fertilizer storage. In studies performed over a three-year period, type 304 SS was observed to be the most beneficial for liquid fertilizer service. For Type 304 SS, carbon steel, and 5052 aluminum (Al), penetration values reported for tanks exposed to commercial liquid fertilizers for almost 2.5 years are in the range of 0.253, 282, and 132 μm , respectively [25]. The samples with high levels of heavy metals contained a lot of organic matter. Heavy metals are retained in the soil as a result of a complicated process involving organic carbon and heavy metals. The soils near dumping grounds are where the samples with the highest concentrations of heavy metals were taken. In this study the range of Fe observed is between 1.22 and 28.65 $\mu\text{g/g}$ [26].

2. MATERIALS AND METHODS

2.1. Site Selection

The study area is located at an elevation of around 633 meters (2077 feet) above sea level, almost in the middle of the State's geographic region. The Kannad city, which has 15 dams and seven lakes, has the most dams in Maharashtra. The town is located in Aurangabad district which lies in Marathwada region of Maharashtra with precise coordinates are 20°27' North and 75° 13' East. A. In the Gautala Sanctuary region in Kannad, teak and sandalwood are primarily found. From Kannad, there are 211 km of the Mumbai-Nagpur State Highway and the Dhule-Solapur National Highway.

The samples are collected from various prime locations of the city having wastes on open ground, nearby roads, and residential areas.

The neighborhood was troubled by a number of issues, including unpleasant smell, insects, vermin, rats, and mosquitoes. Residents were affected with numerous diseases as a direct consequence. A total of 10 samples are collected from residential, industrial, and commercial sites areas in April 2022 as shown in Table 1. Using the appropriate digging instrument, half of each type of site's sample is taken from the top layer (0–5 cm) and half from the subsurface (15–20 cm). About 500 g of soil sample was collected from each location.

2.2. Coupon Specimen and Preparation

Soil samples were air dried for two days and kept in oven for 4 h at 60°C. The dried samples were then disaggregated with mortar and pestle and sieved through 2 mm sieve. Weighing of the sample was carried out using analytical balance with precision as low as 0.0001 g. Soil samples of 0.5 g of each were taken in 100 mL beaker and digested with 10 mL of aquaregia on hot plate for 1 h after evaporation to near dryness the residue were dissolved in 10 mL of 2% nitric acid, filtered with Whatman filter paper No. 41 and then diluted to 100 mL with double distilled water. The samples were organized with proper labels (Sample ID, Sampling time, and location) and kept in polyethylene bags carefully. The bags were labeled as N1, N2, N3 up to N10. The pre-weighed coupons were buried in soil samples. The coupons were retrieved from the samples after specified durations then cleaned, washed, and dried as recommended in the standard procedure of ASTM G1-90 [27] and reweighed. The samples are prepared for additional examination.

Ferrous alloys like MS, SS-304, and non-ferrous metal Al were used for corrosion studies. Rectangular strips of 5 × 1 × 0.1 cm were used in the laboratory weight loss corrosion test method [28]. The hole of 2 mm was drilled in the corrosion coupons near one end for mounting. A few of these coupons were chosen for elemental composition analysis. The elemental composition analysis was determined using an optical emission spectrometer (Foundry Master, Germany) [29].

MS, SS304 and Al Metal typically have the following elemental chemical composition is presented in Table 2.

Similarly, the corrosion study of metals and alloys in soils was carried according to the standard procedure of ASTM G162-99 [28]. The cleaning agent used for MS is 5 mL of con. HCl (Sp.gravity 1.19) + 1 g Sb₂O₃ diluted to 1L with glass distilled water. The cleaning agent for S.S.304 is 5 mL of conn. HNO₃ (Sp.gravity 1.42) diluted to 1L with glass distilled water. The cleaning agent for the Al is 5 mL con. H₃PO₄ (Sp. gravity 1.69) + 1 g chromium Trioxide diluted to 1 L with glass distilled water.

2.3. CR Determination

Physical analysis of soils and mechanical analysis of selected soil samples were also determined. The study was performed to analyze the CR for MS, SS304, and Al strip coupons buried in soil samples for a various time durations.

The weight loss was recorded for each sample. The same procedure was followed for 12, 24, 48 and 96 h. Duplicate experiments were performed in each case and the mean value of the weight loss has been recorded. All the experiments were carried out in the laboratory of room temperature. The CR in each case was calculated using the formula,

$$\text{CR} \left(\text{mg dm}^{-2} \text{hr}^{-1} \right) = \frac{W_i - W_f \times K}{A \times T}$$

W_i = Weight of coupon before corrosion in gm.

W_f = Weight of coupon after corrosion in gm.

A = Geometric area of the coupon.

T = Time of exposure in hours.

K = 2.4×10^6

Table 1: Selected sites area types.

Sample No	Area type
N1	Residential area
N2	Residential area
N3	Residential and Industrial area
N4	Industrial area Opposite
N5	Residential area
N6	Marshy land
N7	Residential area
N8	Residential area
N9	Residential area
N10	Commercial area

Table 2: Elemental analysis of metals.

Element	MS (%)	SS304	Aluminum
Iron (Fe)	99.39	69.00	0.63
Manganese (Mn)	0.280	2.00	0.092
Carbon (C)	0.063	0.08	
Chromium (Cr)	0.034	18.00	0.007
Copper (Cu)	0.069	-	0.11
Aluminum (Al)	0.042	-	98.59
Magnesium (Mg)	-	-	0.094
Molybdenum (Mo)	0.025	-	-
Nickel (Ni)	0.030	10.00	0.002
Phosphorus (P)	0.016	0.045	-
Silicon (Si)	0.011	0.75	-
Sulphur (S)	0.016	0.030	-
Tin (Sn)	0.003	-	-

Table 3: Physical analysis of soil.

Sample No.	Temperature °C	Redox potential (mv)	Electrical. Cond. $\mu S cm^{-1}$	Salt content (mg lit^{-1})	Moisture (%)	Organic matter %	Resistivity ohm. cm.
N1	29	344	278	181	25.57	0.337	1332
N2	32	243	868	566	29.98	0.489	616
N3	32	173	418	272	24.39	0.62	1256
N4	32	183	381	248	29.30	0.395	2012
N5	32	288	398	259	21.50	0.278	932
N6	32	306	418	272	26.17	0.327	613
N7	32.5	302	305	199	22.35	0.493	1043
N8	32.5	310	299	195	23.53	0.35	1046
N9	32.5	327	623	406	19.60	0.099	1226
N10	32.5	308	498	325	18.10	0.336	1250

3. RESULTS AND DISCUSSION

The study of the physical and mechanical study of the soil samples was done in which Temperature, Redox potential, electrical conductivity, silt content, moisture, organic matter, and resistivity were analyzed and shown in Tables 3 and 4. On retrieval of the coupons after each burial period of 6, 12, 24, 48, and 96 h, the coupons were cleaned and analyzed to determine the metal loss and subsequently, the CR. Data of the CR of sets of all the coupons before and after analysis are shown on Tables 5-7 for the MS, SS304, and Al, respectively. The graphical representation is in Figure 1. The average CR data are shown in Table 8 and the graphical trend is shown in Figure 2.

The results showed that generally, weight loss increased over time while CR decreased. It is found that the average CR decreased with exposure time. In another study, polarization resistant (PR) measurement of CR found that the PR technique overestimated CR but predicted a decrease in CR over time [30]. These studies confirm our findings about CR in the MS, SS304, and Al coupons in this study.

3.1. CR for MS

Average CR for the MS coupons from the site after 6, 12, 24, 48, and 96 hours were 77.22, 33.71, 17.30, 7.58, and 2.82 $mg dm^{-2} hr^{-1}$, respectively. The highest CR is observed in the N2 Sample which is 159.20 $mg dm^{-2} hr^{-1}$ for 6-h duration and the lowest is observed in the N8 sample which was 1.54 $mg dm^{-2} hr^{-1}$ for 96-h duration. Here, we observed a reversed trend of decrease in the CR-at all sites, with respect to the duration of exposure. Table 5 shows the details of CR of MS for each time frame of all samples.

3.2. CR for SS304

Average CR for the SS304 coupons from samples after exposure of 6, 12, 24, 48, and 96 hours were 5.065, 2.128, 1.029, 0.449, and 0.207 $mg dm^{-2} hr^{-1}$, respectively. The highest CR is observed in N2 sample which is 6.17 $mg dm^{-2} hr^{-1}$ for 6-h duration and the lowest is observed in the N2 sample which was 0.11 $mg dm^{-2} hr^{-1}$ for 96-h duration. Here also, we observed a reversed trend of decrease in the CR-at all sites, with respect to duration of exposure as per Figure 2. The details of CR of SS304 for each duration for all samples are shown in Table 6.

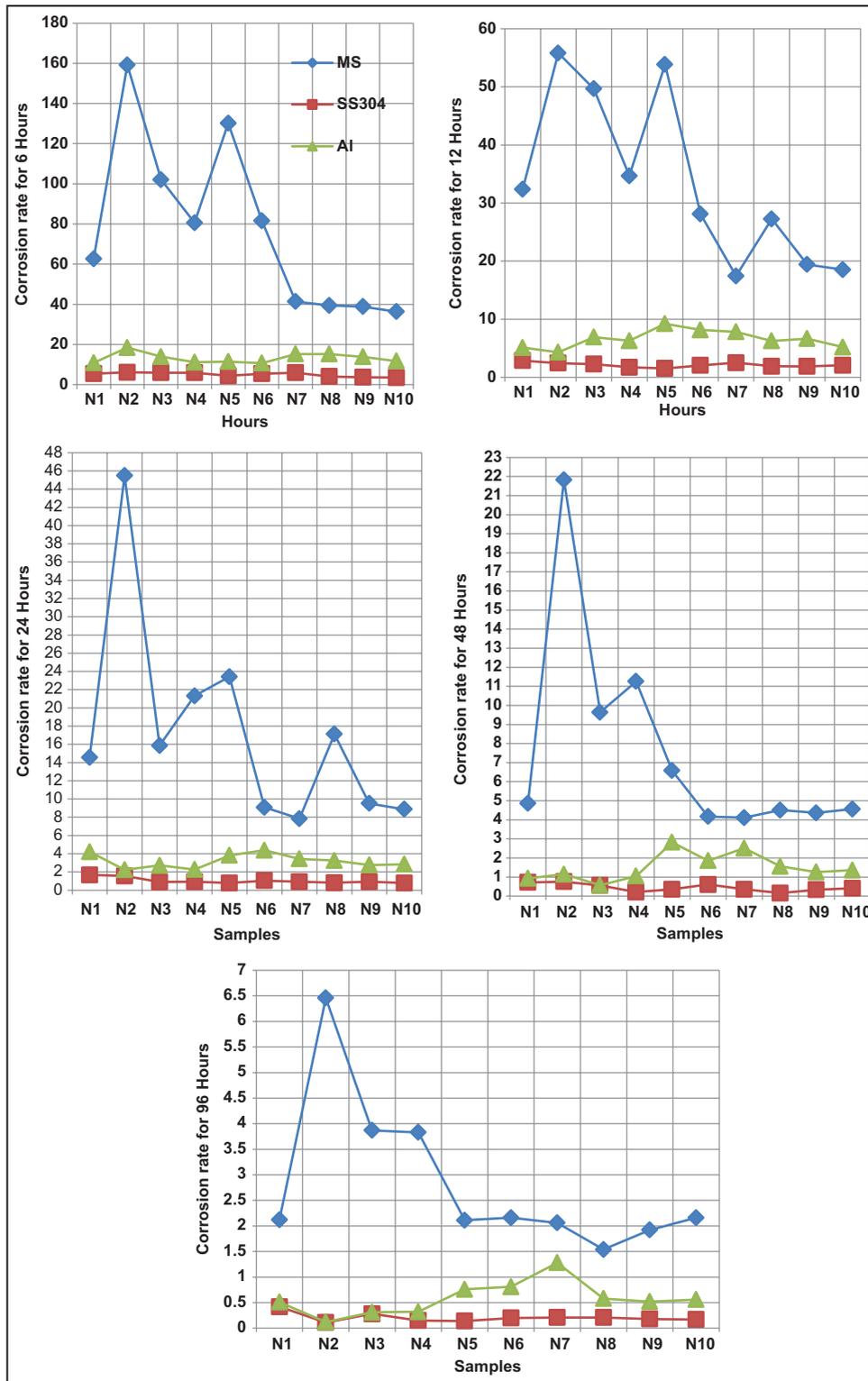


Figure 1: Corrosion Rate of MS, SS304, Al for various durations.

3.3. CR for Al

Average CR for the stainless Al coupons from samples after exposure of 6, 12, 24, 48, and 96 hours were 13.26, 6.59, 3.19, 1.50, and 0.57 mg dm⁻² hr⁻¹, respectively. The highest CR is observed in the N2 Sample which is 18.43 mg dm⁻² hr⁻¹ for 6-h duration and the lowest is observed in the N2 sample which was 0.12 mg dm⁻² hr⁻¹ for 96-h duration. Here also, we noticed a reverse trend of decrease

in the CR-at all sites, with respect to duration of exposure as per Figure 2. Table 7 shows the details of CR of Al of each duration for all samples.

3.4. Average CR

Average CRs for MS for 6, 12, 24, 48, and 96 hours of exposure were 77.22, 33.71, 17.30, 7.58, and 2.82 mg dm⁻² hr⁻¹, respectively.

For SS304, average CRs for 6, 12, 24, 48, and 96 hours of exposure were 5.065, 2.128, 1.029, 0.449, and 0.207 mg dm⁻² hr⁻¹, respectively. Average CRs for Al 6, 12, 24, 48, and 96 hours of exposure were 13.26, 6.59, 3.19, 1.50, 0.57 mg dm⁻² hr⁻¹, respectively, as shown in Table 8 and Figure 2.

These results showed a general pattern of increase in the duration of exposure and a corresponding decrease in CR in all types of corrosion coupons in all soil samples. An inverse proportional

trend seems to exist between the weight loss and CR over time. The average CR was highest in MS and lowest is in SS304. Compare to all Compare to all CR was highest in initial time period which was 6 h and lowest was observed in 96 h. For CR decreasing, the pattern was observed in all tests. There were some spikes in some samples but it does not affect the general decline pattern which observed.

Table 4: Mechanical analysis of soil.

Sample No.	Sand (%)	Silt (%)	Clay (%)	Class of soil.
N1	39.6	50	9.85	Silt loam
N2	22.4	22.5	53.85	Clay
N3	58.63	19.95	18.85	Sandy loam
N4	49.09	41.0	8.85	Loam
N5	20.0	24.0	55.5	Clay
N6	24.0	27.2	48.0	Clay
N7	49.08	30.5	18.85	Loam
N8	41.0	30.0	28.85	Clay loam
N9	51.94	29.0	17.85	Loam
N10	35.57	39.0	24.85	Loam

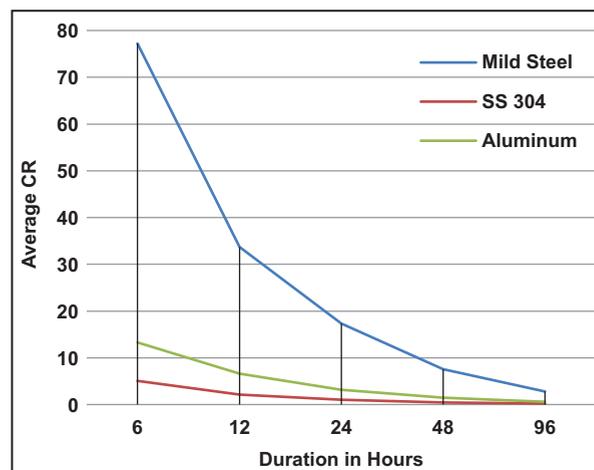


Figure 2: Average corrosion rate of MS, SS304, and Al for various durations.

Table 5: Corrosion rates for MS.

Type of Metal/Alloy	Sample Numbers										
	Hours	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
Mild Steel	6	62.62	159.20	102.1	80.62	130.2	81.56	41.36	39.41	38.86	36.36
	12	32.36	55.82	49.68	34.68	53.87	28.10	17.44	27.26	19.41	18.52
	24	14.55	45.48	15.86	21.31	23.41	9.08	7.84	17.12	9.51	8.87
	48	4.86	21.82	9.64	11.26	6.58	4.17	4.11	4.51	4.36	4.56
	96	2.12	6.46	3.87	3.83	2.11	2.16	2.06	1.54	1.92	2.16

Table 6: Corrosion rates for SS304.

Type of Metal/Alloy	Sample numbers										
	Hours	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
SS 304	6	5.47	6.17	5.97	5.93	4.41	5.48	5.97	4.06	3.68	3.51
	12	2.89	2.45	2.27	1.72	1.53	2.06	2.51	1.90	1.88	2.07
	24	1.67	1.56	0.89	0.92	0.78	1.04	0.92	0.81	0.92	0.78
	48	0.72	0.76	0.56	0.21	0.36	0.61	0.36	0.16	0.34	0.41
	96	0.42	0.11	0.28	0.15	0.14	0.20	0.21	0.21	0.18	0.17

Table 7: Corrosion rates for Al.

Type of Metal/Alloy	Sample numbers										
	Hours	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
Aluminum	6	10.87	18.43	13.95	11.16	11.46	10.72	15.26	15.22	13.84	11.73
	12	5.12	4.32	6.91	6.28	9.22	8.16	7.82	6.27	6.65	5.21
	24	4.22	2.24	2.72	2.26	3.81	4.38	3.43	3.25	2.76	2.85
	48	0.93	1.15	0.57	1.05	2.82	1.86	2.51	1.56	1.26	1.36
	96	0.51	0.12	0.31	0.32	0.76	0.81	1.28	0.58	0.52	0.56

Table 8: Average corrosion rate for MS, SS304, Al in various time durations.

Hours	Type of metal		
	Mild steel	SS 304	Aluminum
6	77.22	5.065	13.26
12	33.71	2.128	6.59
24	17.30	1.029	3.19
48	7.58	0.449	1.50
96	2.82	0.207	0.57

4. CONCLUSION

As metals undergo corrosion in soil environment there is the typical trend of weight loss, CR with respect to the duration of exposure of corrosion coupons. There is an inverse relationship in the CR with respect to time. The weight loss keeps increasing but its rate decreases with duration of exposure. The highest CR and weight loss observed at the time when the corrosion process is initiated and the rate of corrosion tends to decline simultaneously.

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