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Influence of Fouling Assemblage on the Corrosion Behaviour of Mild Steel in the Coastal Waters of The Gulf of Mannar, India

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Abstract: Corrosion behaviour and biofouling characteristics of mild steel in three different coastal locations in the Gulf of Mannar, India have been studied over a period of 24 months. Oyster fouling was predominant at Open sea - Tuticorin, while barnacle fouling was dominant at both Mandapam and Harbour - Tuticorin. The rate of corrosion for 24 months exposure period was highest at Mandapam, where fouling was minimal. The surface of the mild steel was characterized by etchings & crevices beneath the hard foulers attached on it, at all the test locations. The depth of crevice caused by hard foulers was higher at Open sea - Tuticorin followed by Harbour - Tuticorin and Mandapam. The loss in ultimate tensile strength was more in Open sea - Tuticorin than the other two locations. Corrosion behaviour of mild steel is discussed based on the variation in the biofouling assemblage at the three test locations.

Keywords: mild steel; coastal waters; crevice corrosion; biofouling; ultimate tensile strength; fouling assemblage; corrosion behaviour

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1 Introduction

Corrosion in the hostile marine environment will continue to be a problem of major importance to marine engineers and designers. When materials are submerged in the sea, the objects not only soon become covered with marine growth but also certain species of marine organisms accelerate corrosion (Palanichamy *et al*. 2012). It is commonly recognized by investigators worldwide that dissolved organics and the living component of seawater play a crucial role in marine corrosion (Baboian, 2005). The attachment of marine organisms on the surface of metals and metal alloys could be an important contributing factor in the complex corrosion process by producing local changes in dissolved oxygen concentration, pH and oxidation-reduction potential (Pipe, 1981).

Industrialization and urbanization of the cities along the coastal region over the years have made the environment more aggressive in terms of both pollution and corrosion. This fact necessitates, in the instance, greater knowledge on the behaviour of materials in coastal seawater. The chemical and physical properties of natural seawater, which affect corrosion of metals have been well documented (Compton, 1970; Dexter and Culberson, 1980; Schumacher, 1979; Palanichamy *et al*. 2012). Variations in the chemistry of open ocean seawater may influence the corrosion rate of engineering alloys with season and location, but they are unlikely to produce sharp changes in either corrosion mechanism or rate (Zayed *et al*. 2005). On the other hand in the coastal waters, changes that take place over periods of hours to days can occur as a result of point inputs of various chemical pollutants. These effects can lead to sharp chemical gradients over short distances on a temporary or more continuous basis, which will affect the performance of marine engineering alloys. Long-time materials performance in the marine environment reveals remarkable consistency in the corrosion of many engineering alloys in open ocean waters regardless of geographical location. However, LaQue (1949) and Ijsseling (1989) have suggested that large deviations can occur locally in coastal and/or polluted areas. Studies by Palanichamy and Rajendran (2000) have indicated that local condition of coastal water quality can differ significantly as a result of industrial pollution. The effect of pollutants introduced into the coastal waters on the corrosion of marine engineering alloys is not fully understood. In order to obtain realistic corrosion data, these effects should be taken into account.

The studies mentioned above are clear indications that local water quality can differ significantly from open ocean which can produce anomalous corrosion behavior of the common engineering alloys. There is also some evidence in the literature that local pollution can have a strong effect on the type and extent of fouling (Swami and Udayakumar, 2010) which, in turn, can affect the performance of engineering alloys (Palanichamy *et al*. 2012). Although data on the performance of engineering materials in polluted waters is rather limited, they nevertheless strongly suggest that corrosion data from open ocean environments are unlikely to be relevant for service of the alloys in coastal seawater locations that receive significant amounts of pollutants. Unfortunately, data on materials performance in Indian waters are mainly limited to open ocean conditions.

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Thorough scrutiny of literature reveals that there is only scanty information on the corrosion and biofouling characteristics of mild steel in coastal seawater. Further, no comprehensive information is available with respect to simultaneous investigations on the above subject, for different coastal locations. Mild steel being the most versatile, least expensive and widely used engineering material, has found extensive marine application in various industries, viz. nuclear power and fossil fuel power plant, navy, shipping, transportation, chemical processing, petroleum production and refining, pipelines, construction, etc. Hence in this study an attempt has been made to investigate the relationship between the variations in the fouling assemblage and corrosion behaviour of mild steel, simultaneously at three different coastal locations in the Gulf of Mannar, India, which is first of its kind in the literature of Indian waters.

2 Experiment

2.1 Test locations

Three different test locations were chosen in the Gulf of Mannar (Bay of Bengal), India on the basis of available data (Palanichamy and Rajendran, 2000). The coastal waters of Tuticorin (8°8'N; 78°13'E) are relatively polluted compared to the coastal waters of Mandapam (9°16'N;79°9'E). This variation may be due to the harbour and industrial activities along the Tuticorin coast. Two locations were considered in the coastal waters of Tuticorin, one in the open sea and the other in the Harbour, Tuticorin. The depth of the water column in the open sea and in the harbour waters of Tuticorin was 6 and 8 m, respectively, while it was 2 m at the Mandapam site.

2.2 Preparation of metal coupons and exposure to seawater

The mild steel coupons supplied by M/s. Lawrence Metal Industries, Chennai had the following composition: C - 0.1%, Si - 0.07%, Mn - 0.5%, S - 0.05% & balance Fe. The coupons of the size 150×100×2 mm were cut from a sheet, pickled in Clarke's solution as per the ASTM recommendation (1995), washed with soap solution, dried, ground successively with metallographic emery paper of increasing fineness of up to 800 grit (Champion,1952), polished with 1, 0.5 and 0.3 mm alumina slurries (Buehler), weighed to an accuracy of 10^{-4} g, and stored in desiccators until use. The coupons were mounted on wooden rafts using PVC washers and insulated brass bolts and nuts. The rafts were then immersed at a water depth of 1 m below the mean low tide level at the three test locations previously described. The coupons were removed after exposure for 3, 6, 9, 12, 18 and 24 months for the evaluation of corrosion and fouling.

2.3 Specimen preparation and tensile strength measurement

Standard plate-type rectangular tension test specimens with a cross sectional area of 20 mm^2 were prepared in triplicate as per the ASTM Test Method E8 (ASTM 1985a). These specimens received the same surface preparation, mounting and immersion procedures as described above, and were removed after exposure for 12 and 24 months. The tensile strength (ultimate tensile strength) of the as-received and seawater exposed mild steel specimens were measured using a Universal Testing Machine (Universal 2001, Model No. 60). From the obtained load for each specimen, the ultimate tensile strength was calculated by dividing the maximum force carried by the specimen during the tension test by the original cross-sectional area of the specimen, and expressed as megapascals (MPa).

2.4 Characterization of fouling and corrosion

The biomass i.e. fouling load formed on metal coupons over the study period was scrapped and dried to a constant weight at 100°C and weighed to an accuracy of 10^{-4} g. The fouling load was expressed as kg m^{-2} and each value is the mean of triplicate. The fouling characteristics of the mild steel were also studied in terms of the numbers of settled organisms, group-wise occurrence of macrofouling organisms and community development pattern. Fouling organisms were identified to genus and species levels following previous records from the study regions (Maruthamuthu *et al*. 1990; Eashwar *et al*. 1991; Palanichamy *et al*. 2012). After scraping the biomass, the corrosion products were removed using recommended pickling solutions, i.e Clarke's solution. The corrosion rates were determined by gravimetric method and expressed as mmpy and each value is the mean of triplicate coupons. The size and depth of the crevices were measured using a high-resolution microscope (ASTM, 1985b; Metals Handbook, 1987). Digital images of the coupons were obtained before and after the removal of fouling and corrosion products after exposure for 12 and 24 months.

2.5 Seawater analysis

Subsurface seawater was collected from the three test locations on a quarterly basis during the 24 month study period using a Hydro-Bios (Kiel) water sampler. Analyses were carried out following the standard procedures (Strickland and Parsons, 1972) which included general physicochemical parameters (salinity, dissolved Oxygen, pH), dissolved nutrients and major ions. Heavy metals in the water samples were extracted following APDC-MIBK pre-concentration procedure (Brooks *et al*., 1967) and estimated on an atomic absorption spectrometer (GBC 932 Plus).

2.6 Statistical analyses

One way ANOVA was performed on Mircocal ORIGIN software to analyze statistical significance among selected water quality parameters for the three test locations. One way ANOVA was also performed for evaluating the statistical significance of corrosion rates and fouling load data among the three test locations for 12 and 24 months exposure. Linear regression fit was computed for all the 18 sets of the mean values of fouling load and corrosion rate data obtained during the entire study period.

3 Results

3.1 Physicochemical characteristics of seawater

The mean values of physicochemical parameters of seawaters of 1) Open sea - Tuticorin, 2) Harbour - Tuticorin and 3) Mandapam are presented in Table 1. In general the values of the water quality parameters were found to be normal, and did not show much seasonal variation during the study period. Hence the mean values of the eight quarters are taken for consideration. The values of heavy metals like copper, cadmium and mercury were found to be statistically higher at Tuticorin waters when compared to that at Mandapam water ($p < 0.001$). Among the different parameters, nitrate, silicate and ammonia were higher at Tuticorin (both in the open sea and harbour locations) than at Mandapam on a statistically significant basis ($p < 0.001$).

3.2 Biofouling community development pattern

Generally the population density was found to increase with duration of exposure. It is worth mentioning that among the three locations, the surfaces of the 3, 6 & 9 months exposed coupons were dominated by oysters' fouling at Open sea - Tuticorin, whereas at Mandapam and Harbour - Tuticorin**,** barnacles were the dominant fouling organism. However, polychaetes were the second dominating group for 3 months in the Harbour – Tuticorin**.** On contrary, no polychaete fouling was recorded on the coupons that were exposed to Open sea - Tuticorin up to 9 months. Algae and compound ascidians were the other identified fouling organisms at all the three study locations. The common fouling organisms recorded on 12 months exposure were barnacles, oysters, ascidians, bryozoans, algae and polychaetes, at all the three locations.

The major fouling organisms recorded on 18 & 24 months exposure were oyster, barnacles, ascidians & bryozoan, among them, oyster fouling was predominant at Open sea - Tuticorin, while the major fouling organisms recorded at Harbour - Tuticorin were oyster, barnacles, ascidians & bryozoan, among them, barnacle fouling was predominant. The sponge fouling was restricted to Mandapam, while bryozoan was found absent and polychaete was restricted to Harbour - Tuticorin.

Over the period of study, 19 - 35 algal species were recorded at Mandapam, while it was 13 - 19 at Tuticorin. The algal species such as *Ulva lactuca, Caulerpa racemosa & Gracilaria edulis* were found to be common at all the three locations throughout the study period. Bryozoan fouling could be noticed after 9 months exposure at Open sea-Tuticorin and on 9 & 12 months exposures at Mandapam. But, it could be observed after 18 months at Harbour-Tuticorin. As high as 10 species of polychaete worms were found on 12 & 24 months exposure at all the three locations. Rare occurrence of sponge fouling could be noticed on 18 months at Open sea - Tuticorin & Mandapam. Barnacle fouling was round the year phenomena at all the three test locations.

3.3 Quantification of fouling community development pattern

The quantitative fouling community development pattern on mild steel exposed to seawater for 3,6,9,12,18 & 24 months are given in Table 2. The numerical density and surface coverage by organisms reveal that oyster fouling was found dominant at Open sea - Tuticorin (Fig. 1a & 2a) and barnacle fouling at Harbour - Tuticorin (Fig. 3a & 4a) & Mandapam (Fig. 5a & 6a). The numerical density of polychaete worms was in the order: Harbour - Tuticorin > Open sea - Tuticorin > Mandapam, while algal fouling was in the order of Mandapam > Open sea - Tuticorin > Harbour - Tuticorin. Dense fouling by compound ascidian was observed at Mandapam. The maximum density of bryozoan fouling could be noticed at Mandapam on 9 months exposure, whereas it was sparse at Tuticorin waters throughout the study period.

3.4 Fouling load

The fouling load on mild steel exposed to seawater at three test locations for 24 months are illustrated in Fig .7. The fouling load on mild steel showed a gradual increase up to 6 months, after registering a slight decrease at the end of 9^{th} month, the fouling load kept increasing steadily till the end of the 24 months exposure period in Tuticorin waters. On contrary, decrease in fouling load was evident from 12 months onwards at Mandapam. The statistical analysis by One-Way ANOVA for fouling load (Table-3) reveals that the mean fouling loads were significantly different between any two test locations at 0.05 level for 12 & 24 months exposure, excepting between Open sea - Tuticorin & Harbour - Tuticorin, for 24 months.

3.5 Impact of fouling on the surface of mild steel

The surface is characterized by etchings & crevices beneath the hard foulers attached on it, at all the three locations, which are illustrated in Figures 1b and 2b for Open sea - Tuticorin, Figures 3b and 4b for Harbour - Tuticorin and Figures 5b and 6b for Mandapam. Fig.8 shows the percent crevice attack & crevice density of mild steel exposed in seawater. It is evident from the figure that the surfaces of the mild steel experienced increase in density and size of the crevices, over the period of time. The depth of crevice caused by such hard foulers (data not shown in the figure) is in the order of Open sea - Tuticorin (50 - 1500 μm) > Harbour - Tuticorin (50 - 1200 μm) > Mandapam (50 - 800 μm).

3.6 Corrosion rate

Fig. 9 shows a marked decrease in the corrosion rate of mild steel for Open sea - Tuticorin over the period of time and a gradual decrease in the corrosion rate for other two locations. Among the three test locations, the 3 months exposure of mild steel experienced higher corrosion rate (0.412 mmpy) at Open sea - Tuticorin. The magnitude of corrosion rates of mild steel were more or less same at

Harbour - Tuticorin (0.192 mmpy) and Mandapam (0.188 mmpy) for 3 months exposure. It is evident from the figure that up to 18 months period the corrosion rate at Mandapam was found to be lower than those of Tuticorin waters. At the end of 24 months, the corrosion rate of mild steel was in the order of Mandapam (0.122 mmpy) > Open sea - Tuticorin (0.113 mmpy) > Harbour - Tuticorin (0.106 mmpy). The statistical analysis by One-Way ANOVA for corrosion rate data (Table 3) reveals that the mean corrosion rates were significantly different between any two test locations at 0.05 level for 12 months exposure.

Table 1 Seawater quality parameters for the three locations showing the mean values (n = 8) and their SDs

Parameters	Open sea -Tuticorin		Harbour- Tuticorin		Mandapam	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Salinity ‰	35.00	0.74	34.70	0.32517	34.35	0.2144
pH	8.1	0.113389	7.9	0.10351	8.1	0.133631
Dissolved Oxygen (mL·L^{-1})	4.85	0.265922	4.40	0.136277	4.20	0.261186
Inorganic Phosphate (µmol·L^{-1})	0.725	0.074066	0.701	0.058642	0.78	0.086437
Total Phosphorous (µmol·L^{-1})	3.27	1.195894	2.99	1.019448	6.82	2.349024
Nitrite (µmol·L^{-1})	0.017	0.000983	0.016	0.002371	0.013	0.00117
Nitrate (µmol·L^{-1})	4.37	0.297	3.75	0.283	2.75	0.415
Silicate (µmol·L^{-1})	18.83	2.76	28.37	7.07	12.37	1.38
Ammonia (µmol·L^{-1})	2.25	0.134164	2.15	0.262552	1.25	0.260832
Calcium (mg·L^{-1})	400	19.8206	400	10.03567	375	20.52873
Magnesium (mg·L^{-1})	1275	97.24784	1275	81.19641	1225	87.62746
Copper (µg·L^{-1})	2.7	0.47	3.2	0.81	0.2	0.04
Cadmium ((µg·L^{-1})	1.30	0.217	1.42	0.254	0.95	0.0609
Lead ((µg·L^{-1})	14	0.7278	21	4.876132	12	3.494281
Iron ((µg·L^{-1})	54.0	15.928	55.82	13.05469	56.90	5.260092
Manganese ((µg·L^{-1})	5.50	0.790569	5.47	1.170738	5.72	0.85552
Zinc (µg·L^{-1})	1.570	0.5947	1.513	0.158034	1.366	0.206116
Mercury (µg·L^{-1})	1.196	0.234379	0.72667	0.110151	0.48333	0.307463

Fig. 1 (a) Fouling development; (b) impact of fouling on mild steel exposed for 12 months at Open sea - Tuticorin. Scale bar = 25 mm on both images

3.7 Loss in tensile strength of mild steel

The tensile strength (ultimate tensile strength) of both (i) as received and (ii) seawater exposed mild steel, are shown in Fig. 10. In general the % loss of tensile strength increases with time, at all the test locations. The loss in ultimate tensile strength of mild steel was 20.83% & 31.25% for 12 and 24 months at Open sea - Tuticorin, 16.66% & 21.88% for 12 and 24 months at Harbour - Tuticorin and 12.5% & 20.83% for 12 and 24 months at Mandapam, respectively. The results indicate that the loss in tensile strength was more in Open sea - Tuticorin than the other two locations.

Table 2 Quantification of fouling community development pattern on mild steel exposed to seawater over a period of 24 months

Period /month	Open sea - Tuticorin		Harbour - Tuticorin		Mandapam	
	Density /(No. m^{-2})	Surface coverage /%	Density /(No. m^{-2})	Surface coverage /%	Density /(No. m^{-2})	Surface coverage /%
Barnacle						
3	333	25	1200	70	833	50
6	600	30	833	80	1533	70
9	600	15	1333	80	2667	50
12	400	6	2167	25	4333	40
18	1000	35	3167	40	1667	25
24	1333	20*	1000	20	2667	30
Oyster						
3	733	45	-	-	100	5
6	733	60	-	-	-	-
9	200	70	-	-	133	15
12	600	75	200	45	67	10
18	400	80	200	15	133	20
24	667	100	400	20	67	5
Polycheates						
3	-	-	333	5	75	5
6	-	-	-	-	67	5
9	-	-	-	-	-	-
12	667	5	1166	10	*	2
18	-	-	-	-	-	-
24	-	-	*	30		-
Algae (predominantly - Green)						
3	sparse	10	sparse	15	sparse	10
6	sparse	10	-	-	Sparse	10
9	sparse	5	-	-	Sparse	10
12	sparse	5	*	5	*	5
18	*	20	-	-	*	25
24	*	20	*	10	*	30
Compound Ascidians						
3	sparse	20	sparse	10	Dense	30
6	-	-	Sparse	20	Sparse	15
9	33	10	33	20	67	10
12	*	5	*	25	*	35
18	*	35	*	20	*	25
24	*	20	-	-	*	40
Bryozoan						
9	-	-	-	-	67	15
12	*	5	-	-	*	8
18	*	8	-	-	-	-

* secondary foulant

Table 3 Statistical analysis by One-Way ANOVA for the corrosion rate and fouling load data of mild steel between any two locations

Test location	Corrosion rate		Fouling load	
	12 months	24 months	12 months	24 months
Open sea - Tuticorin & Harbour - Tuticorin	$F = 0.33803$ $p = 0.59216$*	$F = 0.91875$ $p = 0.39208$	$F = 239.63148$ $p = 1.01643E{-4}$*	$F = 0.96063$ $p = 0.38252$
Harbour - Tuticorin & Mandapam	$F = 34.75532$ $p = 0.00414$*	$F = 4.8$ $p = 0.0936$	$F = 15.57006$ $p = 0.01688$*	$F = 677.55685$ $p = 1.29419E{-5}$*
Mandapam & Open sea - Tuticorin	$F = 37.33636$ $p = 0.00363$*	$F = 1.92857$ $p = 0.23724$	$F = 354.88809$ $p = 4.67578E{-5}$*	$F = 191.05285$ $p = 1.58796E{-4}$*

***significantly different at 0.05 level**

4 Discussion

Marine fouling is strongly influenced by the local environment, which in turn affect the early rate of corrosion (Melchers, 2007). In the present study, fouling load was found to be rather higher at Tuticorin waters when compared to that at Mandapam, after 9 months. Further, the nutrient levels such as nitrite, nitrate, ammonia & silicates were also higher at Tuticorin waters. This observation extends support to the view of Melchers (2007), who reported that the rate of marine growth is known to be a function of water nutrient content. This means that there is a correlation between nutrient levels and fouling load. Impact of fouling on the surface of mild steel exposed to seawater is found to be more severe at Tuticorin waters, particularly at Open sea - Tuticorin, when compared to Mandapam. This can be attributed to the variation in the fouling community. Barnacle fouling was predominant both at Mandapam and Harbour-Tuticorin, whereas oyster fouling was predominant at Open sea - Tuticorin. Though the values of heavy metals like copper, cadmium and mercury were found to be statistically higher at Tuticorin waters when compared to that at Mandapam water, they did not inhibit the fouling growth at Tuticorin waters. The higher corrosion rates (Fig.9) recorded at Open sea - Tuticorin up to 12 months could be due to the localized crevice corrosion that occurred beneath the oyster (Fig.1b) and besides the general corrosion caused by the aggressive nature of the test location. The relative decrease in the corrosion rate observed on 18 & 24 months, could be ascribed to the shielding effect caused by the oyster fouling (Fig.1a & 2a). Relatively algal fouling was predominant at Mandapam, where the levels of nutrients like inorganic phosphate and total phosphorous were found to be appreciable. This extends support to the work of Kuffner and Paul (2001), who demonstrated that phosphorus, could stimulate the algal growth. The study area, Open sea - Tuticorin is located below the offshore platform of CECRI, which is situated near the south breakwater road whose slope is reinforced by boulders. During southwest monsoon (April - October), the site is characterized by severe wave action which renders turbulence, splashing & swirling. The impact of the physical conditions in enhancing oyster fouling has been discussed earlier (Chellam, 1978). Hence, it is presumed that the prevailing conditions would have favoured the settlement and growth of oysters. Also, there is evidence that local pollution can boost the development of certain groups of macrofouling communities (Koryakova *et al*. 2002). Hence it is believed that the prevailing conditions would have favoured the settlement & growth of oysters. The occurrence of the barnacle Balanus tintinnabulum was another cause for the higher fouling load in Tuticorin waters. The relatively low amount of fouling in Mandapam was presumably due to the smaller types of organisms (Balanus amphitrite and Balanus reticulatus) occurring in these waters. Further, the decrease of fouling load at Mandapam particularly after 12 months could be due to the bryozoan fouling which is known to inhibit other macro fouling species (Sutherland, 1976).

The decrease in the corrosion rate values of cumulative exposures of mild steel at all the three locations explicitly implies the protective nature of dense assemblage of fouling organisms which act as a barrier between the metal and the seawater, thereby considerably reducing the diffusion of O2 and also utilizing available O2 for respiration (Little *et al*. 2008). In general, the surfaces of the mild steel experienced increase in density and size of the crevices, over the period of time. The extent of crevice corrosion caused by hard foulers is in the order of Open sea - Tuticorin > Harbour - Tuticorin > Mandapam. The crevice corrosion caused by the hard foulers can be explained that beneath the hard foulers like barnacle, oyster, etc., a condition favouring the creation of anaerobiosis and differential aeration cell, would have resulted in crevice corrosion (Pipe,1981). An inverse relation between corrosion and fouling i.e. less fouling load and higher corrosion rate could be observed at Open sea - Tuticorin during 3 and 6 months exposure. This could be attributed to the wave action, which is characteristic feature of this location. Eashwar *et al*. (1990) reported similar observation that less fouling load and increased corrosion rate during winter months at Mandapam. Regression analysis of the corrosion rate and fouling load data for all six exposure periods at the three test locations (18 sets in all) is given in Fig. 11. The analysis shows a moderately strong negative correlation (R = -0.4223), which is statistically significant (p = 0.08085). This trend is consistent with the observations of many authors who have conducted long-term tests in the sea (LaQue 1949; Southwell *et al*. 1974; Eashwar *et al*. 1990; Luo 2001; de Brito *et al*. 2007; Palanichamy *et al*. 2012).

The corrosion rates of mild steel observed in the present study at Open sea - Tuticorin during 3 (0.412 mmpy) & 6 (0.345 mmpy) months, are comparatively higher than that reported (0.345 - 0.373 mmpy) by Maruthamuthu *et al.* (1993) for monthly exposures at Harbour - Tuticorin. It is explicit that the quarterly and half-yearly rates of corrosion were higher than the monthly rates, which indicates the aggressive nature of the test location. In addition, the fouling load was also rather lower at Open sea - Tuticorin than the Harbour - Tuticorin. In view of the lower fouling load, more surface area of the coupon had maximum access for corrosion attack (Subramanian, 1993), resulting in higher corrosion rate during initial period of exposure. However, in the present study the corrosion rates observed for Harbour - Tuticorin are comparable with those reported by Maruthamuthu *et al.* (1993). Palraj and Venkatachari (2006) reported the quarterly corrosion rate of mild steel for Mandapam water (0.12 - 0.39 mmpy, with an average value of 0.257 mmpy), which is found to be rather higher than the present work (0.198 mmpy) for the same study location. The lower corrosion rate recorded in the present study is mainly due to the comparatively higher fouling load ($0.5-1.7$ kg·m^{-2}) than that ($0.18-0.4$ kg·m^{-2}) reported by Palraj and Venkatachari (2006).

One of the major problems affecting the structural integrity of steel structures is corrosion fatigue cracks, initiated from the randomly distributed pits/crevices on the structure of materials under freely corroding conditions in natural seawater. The steady increase in the values of percentage loss in the ultimate tensile strength can be attributed to the crevice corrosion experienced by the mild steel which is in agreement with the results reported elsewhere (Schumacher, 1979; Xiao *et al*. 1988; Subramanian, 1993; Palanichamy *et al*. 2012). The reduction of ultimate tensile strength for 12 months exposure is supported by the highest values of weight loss corrosion (0.169 mmpy for Open sea - Tuticorin) and maximum values of crevice corrosion (Depth:1500 µm for Open sea -Tuticorin).

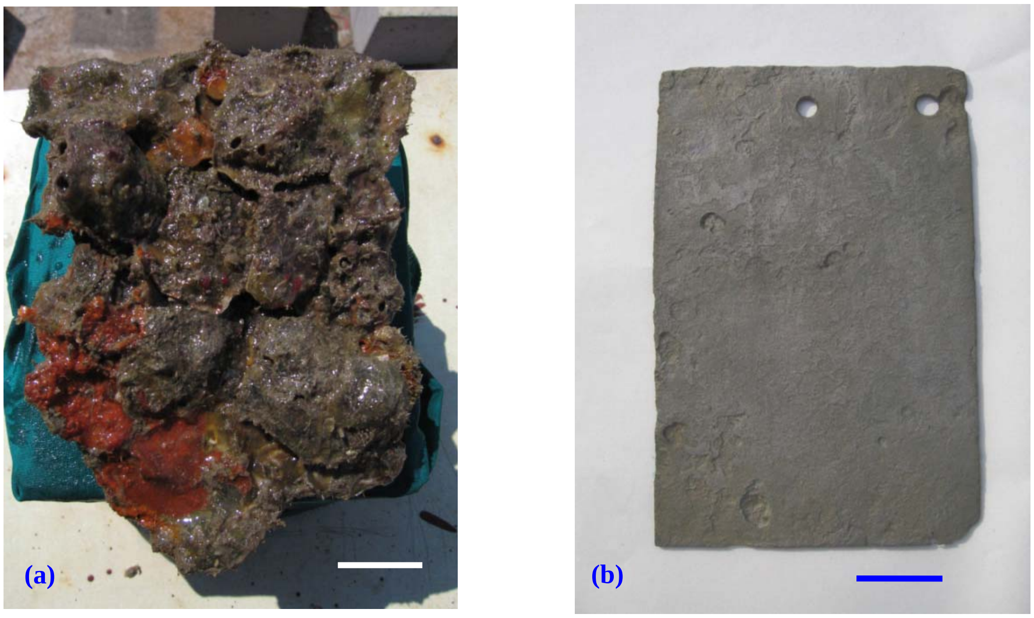


Fig. 2 (a) Fouling development; (b) impact of fouling on mild steel exposed for 24 months at Open sea - Tuticorin. Scale bar = 25 mm on both images

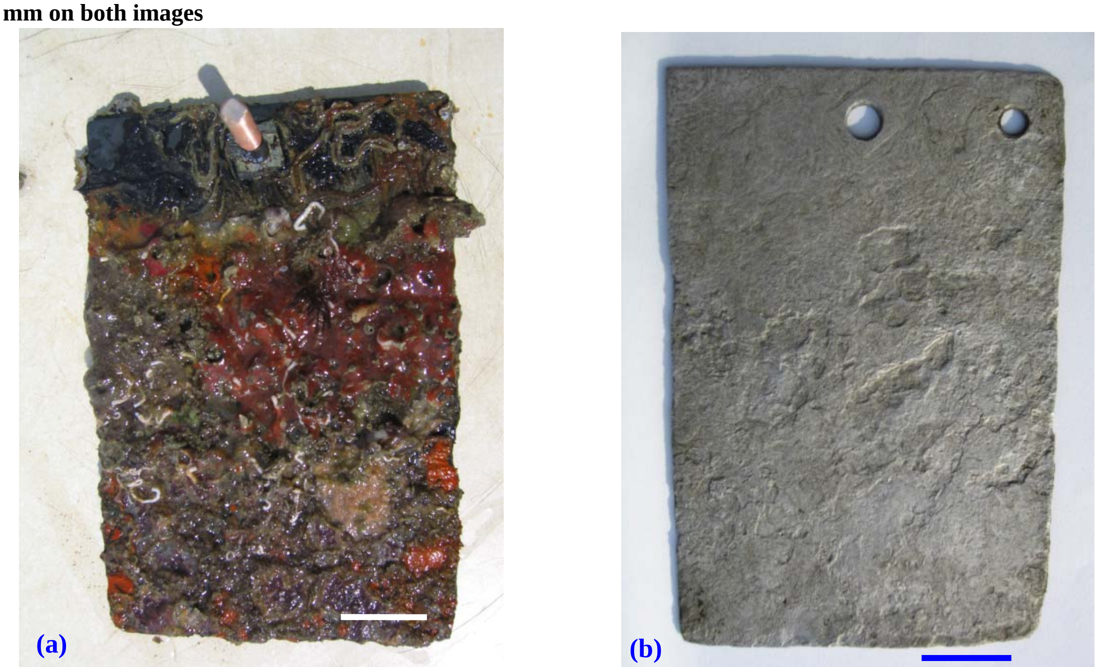


Fig. 3 (a) Fouling development; (b) impact of fouling on mild steel exposed for 12 months at Harbour - Tuticorin. Scale bar = 25 mm on both images

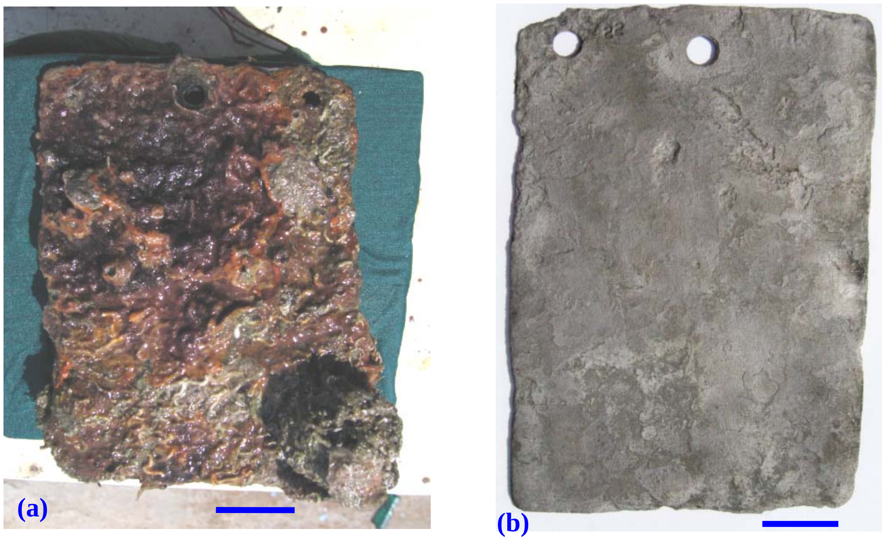


Fig. 4 (a) Fouling development; (b) impact of fouling on mild steel exposed for 24 months at Harbour - Tuticorin. Scale bar = 25 mm on both images

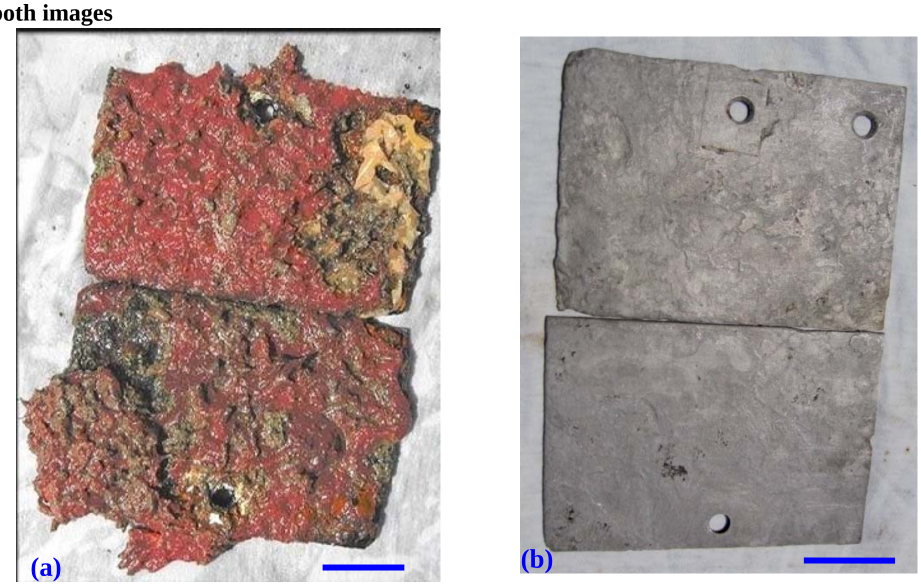


Fig. 5 (a) Fouling development; (b) impact of fouling on mild steel exposed for 12 months at Mandapam. Scale bar = 25 mm on both images

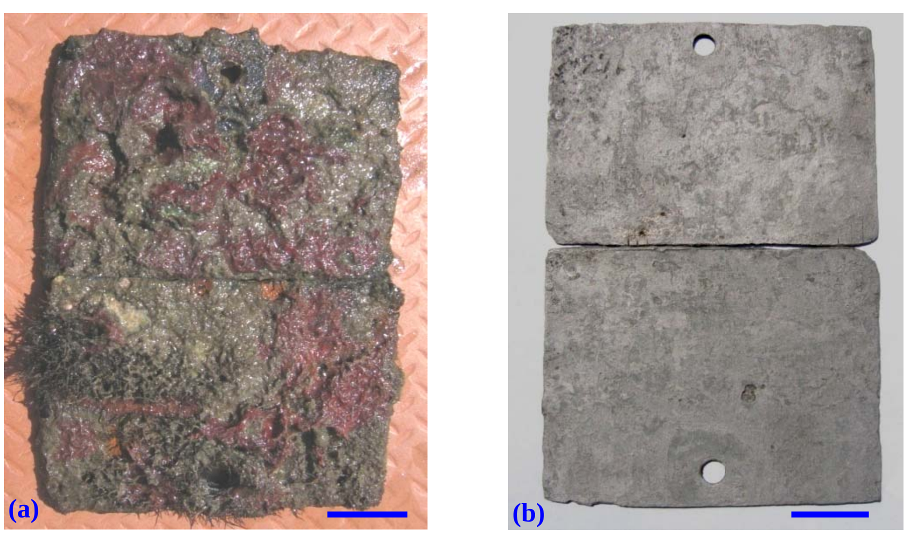


Fig. 6 (a) Fouling development; (b) impact of fouling on mild steel exposed for 24 months at Mandapam. Scale bar = 25 mm on both images

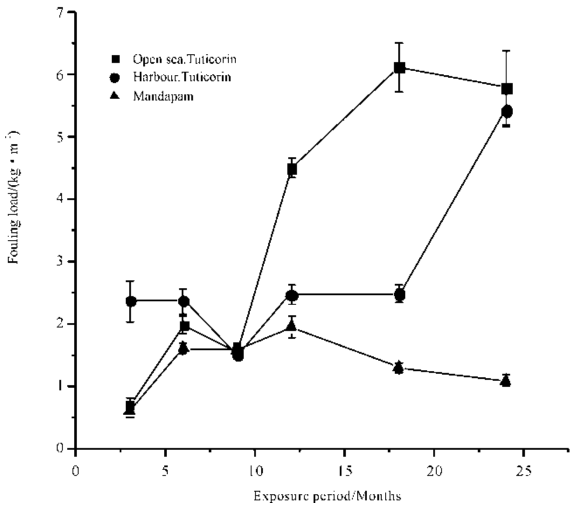
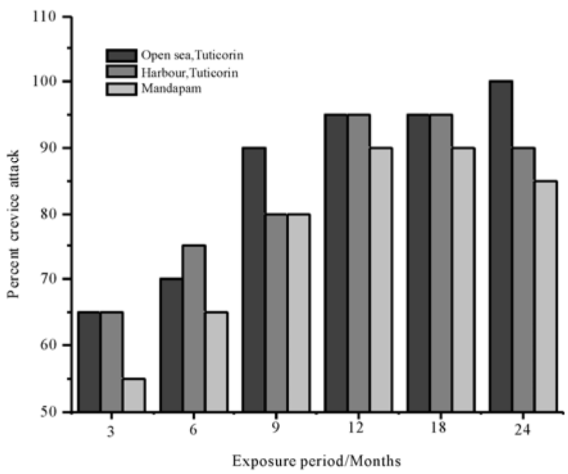
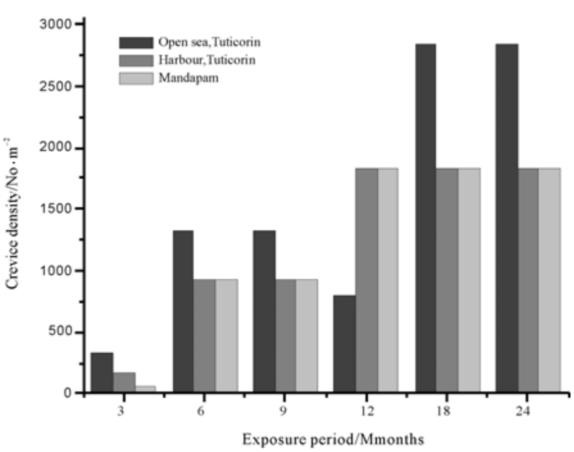


Fig. 7 The fouling load on mild steel exposed to seawater at three test locations over a period of 24 months



(a)



(b)

Fig. 8 The percentage area of attack (a) and crevice density (b) on mild steel with time of immersion at the three test locations

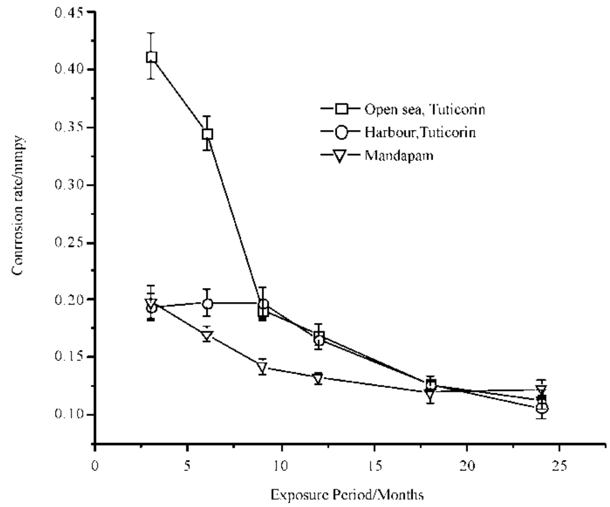


Fig. 9 The corrosion rates of mild steel exposed to seawater at three test locations over a period of 24 months

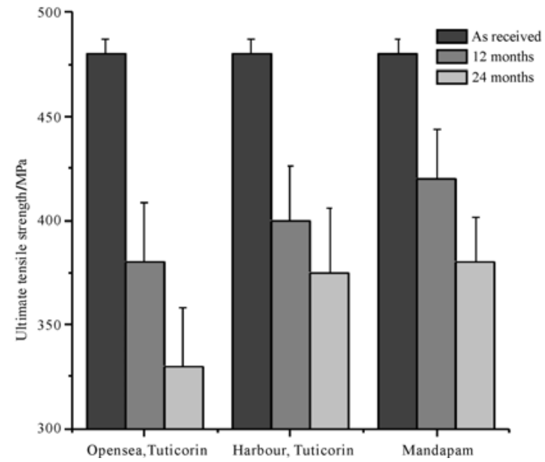


Fig. 10 Loss in ultimate tensile strength of mild steel exposed

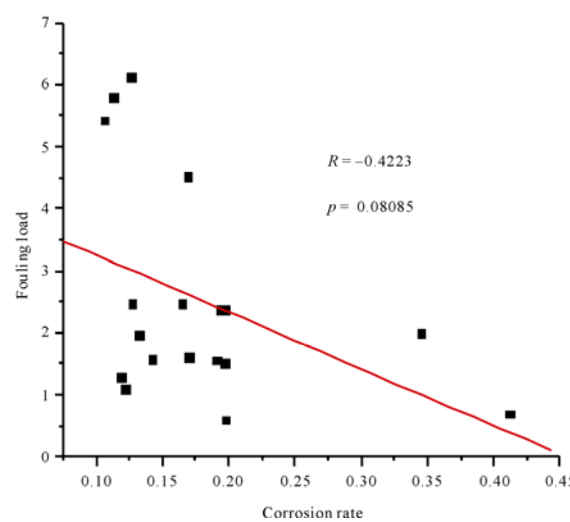


Fig. 11 Regression analysis for all the corrosion rate and fouling load data at the three test locations

5 Conclusions

Barnacle fouling was predominant both at Mandapam and Harbour- Tuticorin, whereas oyster fouling was predominant at Open sea - Tuticorin. The bryozoan foulers inhibited other macro fouling species. The fouling assemblage acted as a barrier and reduced the corrosion rate over the period of time. Thus, the corrosion rate and fouling load data exhibited a statistically significant negative correlation. The rate of corrosion for 24 months exposure period was highest at Mandapam, where fouling was minimal. Hard foulers like oyster and barnacle, induced crevices which resulted in the loss in ultimate tensile strength of mild steel. Among the three test locations, the loss in ultimate tensile strength of mild steel was maximum at Open sea - Tuticorin.

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