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Analysis of the Effects of Corrosion in Marine Heat Exchanger Performance in Two Media

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Abstract This paper investigates the rate of corrosion of cast steel and copper tubes of grades C-1020 and C-642 in marine heat exchangers. The sturdiness of both cast steel and copper depends mostly on the environment they find themselves. Among these are freshwater, seawater and temperature. Both metals were exposed to different concentrations. The effects were investigated using weight loss method and the results from the study showed that cast steel corrodes faster with greater weight loss than copper in all the test media as the corrosion rate for cast steel at 0.000004 M, 0.1 M and 0.2 M concentration ranged from 0.0452mm/yr. – 0.0656mm/yr. and that of copper tested at 0.000004, 0.1M and 0.2M gave corrosion rates from 0.0363mm/yr. – 0.0006mm/yr. The surface analysis carried out with the help of an Inverted metallurgical microscope (IMM) showed the micrographs of the metal surfaces which revealed indications of general corrosion on the specimens and the corrosion impact was observed significantly less in the copper specimen than in the cast steel specimen. The hardness and tensile strength tests were also carried out to further specify the effects of corrosion on the strength of the metals. The difference in hardness and tensile strength between the specimens revealed that the copper specimen was of higher tensile strength and hardness than the cast steel specimen which makes the copper specimen more resistant to corrosion than the cast steel.

Keywords: *heat exchanger, media, surface analysis, hardness test, corrosion rate*

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1. Introduction

The phenomenon of corrosion can be considered as electrochemical or chemical in nature [1]. According to [2], corrosion in metals has a good relation with the operating environment they find themselves. When metals are exposed to oxygen and water, there is loss of electrons which causes corrosion [3,4]. Corrosion is a major worry in the marine environment [5]. It causes serious damage to metals and plants [6,7,8]. Posited that corrosion in metal is a major problem in marine and mechanical components. According to [7], corrosion cost the United Kingdom and the United States of America an estimated $70 billion which accounts for about 4% of their Gross Domestic Product (GDP).

The importance of the heat exchanger to marine engineering applications cannot be over emphasized. [9] Defined the heat exchanger as an equipment which allows the transfer of heat between fluids at different temperatures [10,11]. Heat exchangers are commonly used in diverse industries for different technological purposes in connection with mass and heat transfer. Heat exchangers are also used as temperature profile controls in polyethylene plants [12], where it can be used to warm a cold fluid or to cool a warm fluid or both [15].

The reduction in the performance of the heat exchangers can lead to damage of other equipment and drop in organizational profits and downtimes [12]. According to [13] the performance of heat exchangers wanes with time due to corrosion taking place on the heat transfer surface. [12] Posited that the major cause in reduction of heat exchanger performance is the deposit of irrelevant materials that act upon the heat transfer surface. [14], in their research averred that corrosion also reduces the cross sectional area for heat to be transferred and causes an increase in the resistance to heat transfer across the heat exchanger. The aim of this research is to comparatively determine the effect and rate of corrosion of marine heat exchanger by exposing cast steel (C-1020) and copper (C-642) at room temperature and at different concentrations in freshwater and salt water as possible media.

2. Materials and Method

The method employed in this research in the determination of the effect of corrosion damage on the metals is by estimating the rates of corrosion in different media with gravimetric/weight loss method. The specimen (coupon) was weighed before it was exposed to the solvent. After exposing the specimens in inorganic solvent for a period of 21 days (504 hours or 0.0575 year), they are brought out at intervals of 7days (168 hours/0.0192yr) and corrosion products on the metal were properly cleaned off and reweighed. The weight difference before and after exposure was used as the weight loss and from the weight loss, the corrosion rate of the given specimen was calculated. The solvents used were seawater and freshwater. The fresh water used for this research work was taken from the Nun River, Southern Ijaw L.G.A. Bayelsa State, Nigeria while the seawater was obtained from Elia-Gina River, Ogonokom, Abua/Odual L.G.A. Rivers State, Nigeria. Constituent of seawater and freshwater are as shown in the Table 1.

The Tensile strength and the Brinell hardness of the specimens were tested using the MITECH 320 LEEB hardness tester. Positive Material Identification (PMI) was also used to determine the chemical composition and grades of the specimen used. Finally, the surface of the specimen used was analyzed before and after immersion with the use of the Inverted Metallurgical Microscope (IMM). The equipment used for the PMI test was the Oxford Instrument X-Met 7000 XRF Spectrometer, wire brushes and industrial rags. The X-MET 7000 series has factory settings which are applicable to many measurements.

2.1. Weight Loss/Gravimetric Analysis

The weight loss technique was employed to determine the weight difference of the specimens in order to calculate their rates of corrosion. The coupons were weighed before been exposed to the seawater, of known concentrations of 0.10M to 0.20M with salinity of 4.24mg/liter and freshwater media of 0.23mg/liter and salinity of (0.000004M) for 21 days at room temperature.

After exposure for a stipulated time, corrosion products on the metals were properly cleaned off and reweighed. The weight loss in grams was taken as the difference in the weight of the coupons before and after immersion in the two different test solutions (seawater and freshwater media). The corrosion rate of the given specimen were calculated from the weight loss obtained. The coupons were exposed to the seawater and freshwater in such a way as to reveal a large surface area of the specimen to the media. Each coupon was suspended in a known volume of corrosion media (250ml) through a supporting rod and a thread as shown in Figure 2. This was done to ensure uniform contact of the specimen with the medium. Each beaker was labeled and kept in an isolated place as shown in Figure 1 so as to allow for uniform interaction with the environment.

Table 1. Constituents of Seawater and Freshwater

Constituent	P^H	Salinity	NO_3	Cl	SO_3	Ca	Mg	Na	Fe	K
Seawater	8.11	4.24	7.641	975	54.60	568	142	264	0.54	72
Freshwater	6.25	0.23	0.214	27.0	4.86	18.54	4.50	7.62	–	3.42

Figure 1. The experimental set up specimens and solvents

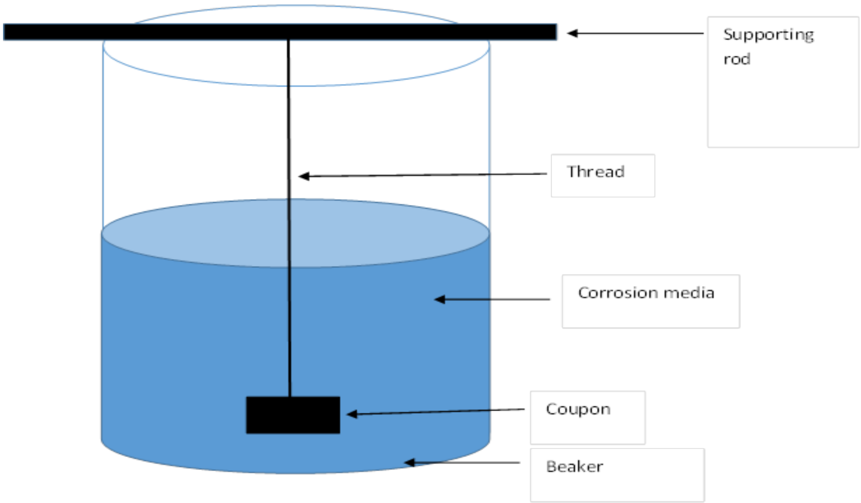

Figure 2. Beaker used for corrosion medium

Figure 3. Ultra-Sensitive Weighing Balance

Since the corrosion rate depends on the weight loss, adequate caution was taken to ensure that the accurate weight was measured to arrive at appropriate result. The weighing balance used for this study is an ultra-sensitive weighing balance which reads values to the 0.00 grams (g) as shown in Figure 3. The specimens were labeled 1, 2, 3 and 4 for both materials selected and weighed accordingly.

2.2. Estimation of Corrosion Rate

Result obtained from the experiment can be referred to a unit of metal surface (mm^2 or cm^2) and sometimes (hour, day, year etc.). Hence, corrosion rate is expressed in g/cm^2.hr or mg/mm^2.day. The corrosion resistance of a metal and the data obtained from the weight losses are converted into an index, which indicates the reduction in metal thickness. Such unit of corrosion resistance measurement is millimeter penetration per year (mm/yr.).

The corrosion rate in absence of inhibitors expressed using millimeter penetration per year (mm.py) is given as follows:

$$\text{Corrosion rate } (C.R) = \frac{Weight\ Loss(W) \times K}{D(\frac{g}{mm^3}) \times A(mm^2) \times T(yr)} \quad (1)$$

Where:
K = Rate Constant (87.6)
ΔW = Weight loss in grams

$$D = \frac{mass(g)}{volume(mm^3)} \quad (2)$$

D = Density of metal (g/mm^3)
A = surface area of metal (mm^2)
T = Time of exposure in yrs.

$$\text{Corrosion rate } (mm.py) = \frac{87.6 \times \Delta W}{D \times A \times T} = \frac{g}{\frac{g}{mm^3} \times mm^2 \times yr} = mm / yr. \quad (3)$$

2.3. Density and Surface Area of Specimen

Rectangular materials of known lengths (L), widths (W) and heights (H) of cast iron and copper were used and the volume, surface areas and densities were calculated as:

$$Volume = L \times W \times H \quad (4)$$

$$Area(A) = L \times W \quad (5)$$

$$\text{Density} = \frac{Mass(g)}{Volume(mm^3)}. \quad (6)$$

Therefore, densities of Cast Steel and Copper were obtained as 7.822 g/mm^3 and 4.727 g/mm^3.

Table 2. Weights, Shapes, Sizes and Areas of the Specimens used for the Experimentation

Cast Steel (Rectangular)					Copper(Rectangular)				
Specimen	Weight (g)	Length (mm)	Width (mm)	Area (mm^2)	Specimen	Weight (g)	Length (mm)	Width (mm)	Area (mm^2)
1	12.4	31.5	15	472.5	1	2	30.9	17.8	550.02
2	15.61	-	-	-	2	1.97	-	-	-
3	14.79				3	1.96	-	-	-
4	13.4				4	1.96	-		-

Figure 4. Experimental set up for the Hardness and Tensile strength test

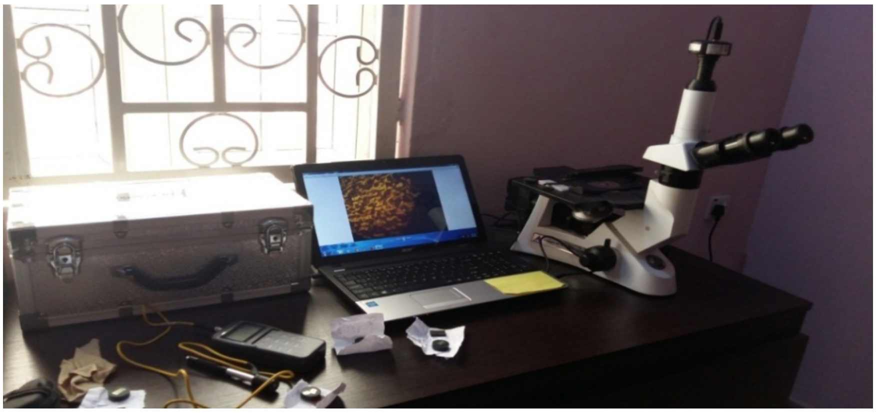

Figure 5. Experimental set up for scanning of the specimens using the Inverted Metallurgical Microscope

Table 3. Experimental data for copper coupons weight obtained at room temperature for 21 days

Concentration (M)	Original weight (g)	Week 1 weight (0.0192yr)	Week 2 weight (0.0384yr)	Week 3 weight (0.0576yr)
0.000004M	1.960	1.960	1.960	1.950
0.10M	1.920	1.900	1.880	1.850
0.20M	1.970	1.950	1.930	1.910

Table 4. Experimental data for Cast Steel coupons weight obtained at room temperature for 21 days

Concentration (M)	Original weight (g)	Week 1 weight (0.0192yr)	Week 2 weight (0.0384yr)	Week 3 weight (0.0576yr)
0.000004	14.79	14.75	14.70	14.63
0.10	13.40	13.37	13.31	13.25
0.20	15.61	15.58	15.54	15.51

Table 5. Weight Losses and Corrosion Rates Cast Steel at Different Concentrations

Concentration (M)	Original Weight (g)	Week 1 Weight (0.0192yr)	Weight Loss(g) (0.0192yr)	Corrosion Rate Week 1 (mm/yr.)	Week 2 Weight (0.0384yr)	Weight Loss(g) (0.0384yr)	Corrosion Rate Week 2 (mm/yr.)	Week 3 Weight (0.0576yr)	Weight Loss(g) (0.0576yr)	Corrosion Rate Week 3 (mm/yr.)
0.000004	14.79	14.75	0.04	0.0493	14.70	0.09	0.0555	14.63	0.16	0.0658
0.10	13.40	13.37	0.03	0.0369	13.31	0.09	0.0555	13.25	0.15	0.0617
0.20	15.61	15.58	0.03	0.0369	15.54	0.07	0.0432	0.11	0.11	0.0452

Table 6. Weight Losses and Corrosion Rates of Copper at Different Concentrations

Concentration (M)	Original Weight (g)	Week 1 Weight (0.0192yr)	Weight Loss(g) (0.0192yr)	Corrosion Rate Week 1 (mm/yr.)	Week 2 Weight (0.0384yr)	Weight Loss(g) (0.0384yr)	Corrosion Rate Week 2 (mm/yr.)	Week 3 Weight (0.0576yr)	Weight Loss(g) (0.0576yr)	Corrosion Rate Week 3 (mm/yr.)
0.000004	1.96	1.96	0.00	0.0000	1.96	0.00	0.000	1.95	0.01	0.0006
0.10	1.92	1.90	0.02	0.0351	1.88	0.04	0.0351	1.85	0.07	0.0409
0.20	1.97	1.95	0.02	0.0351	1.93	0.04	0.0351	1.91	0.06	0.0363

2.4. Hardness and Tensile Strength Testing

The hardness and tensile strength for both specimens were determined before and after the immersion so as to show the effect of corrosion on them. The equipment used for this test is MH 320 Mitech mobile hardness tester with automatic loading system as shown in Figure 4.

3. Result and Discussion

3.1. Result

The weight loss and corrosion rate of cast steel and copper coupons with respect to their various test media at room temperature have been analyzed and the results presented in Table 3 and Table 4. Also, the weight losses and corrosion rates for cast steel and copper specimens were calculated for 0.000004M of freshwater; 0.10M and 0.20M of seawater as seen in Table 5 and Table 6. Table 3 and Table 4 showed that the loss in weight of both specimens increased with longer exposure time. A careful examination and comparison of both specimen revealed that the weight loss was higher in the cast steel coupon than that of the copper coupon.

The effects and variations of the exposure time of the coupons in freshwater with the rate of corrosion can be seen in Figure 6 and Figure 7. The figures illustrate the fact that cast steel corrodes faster than copper when both are immersed in water of same concentration for specific periods of time. The effect of immersion time and the weight loss of both specimens in fresh water and sea water at room temperature at different concentrations have been studied and represented in Figure 8 and Figure 9.

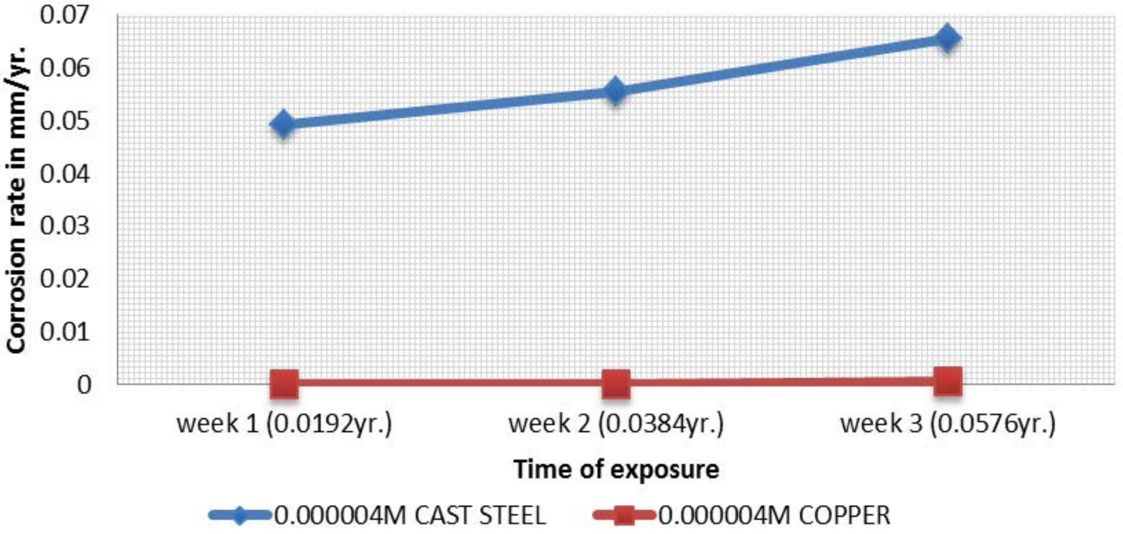

Figure 6. Corrosion Rate versus Time of Exposure of Cast Steel and Copper in 0.000004M of Freshwater

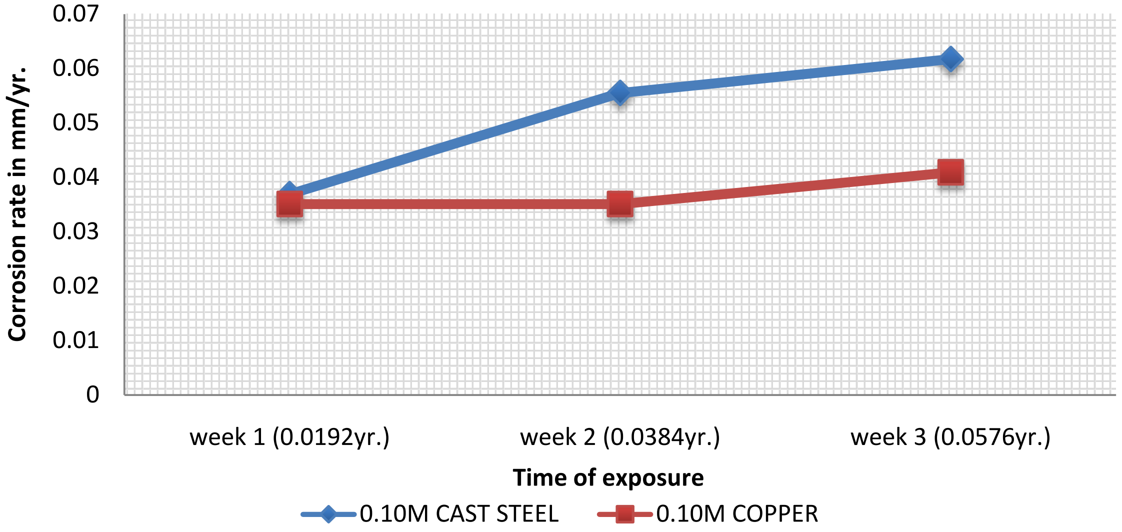

Figure 7. Corrosion Rate versus Exposure Time of Cast Steel and Copper in 0.1M of Sea Water

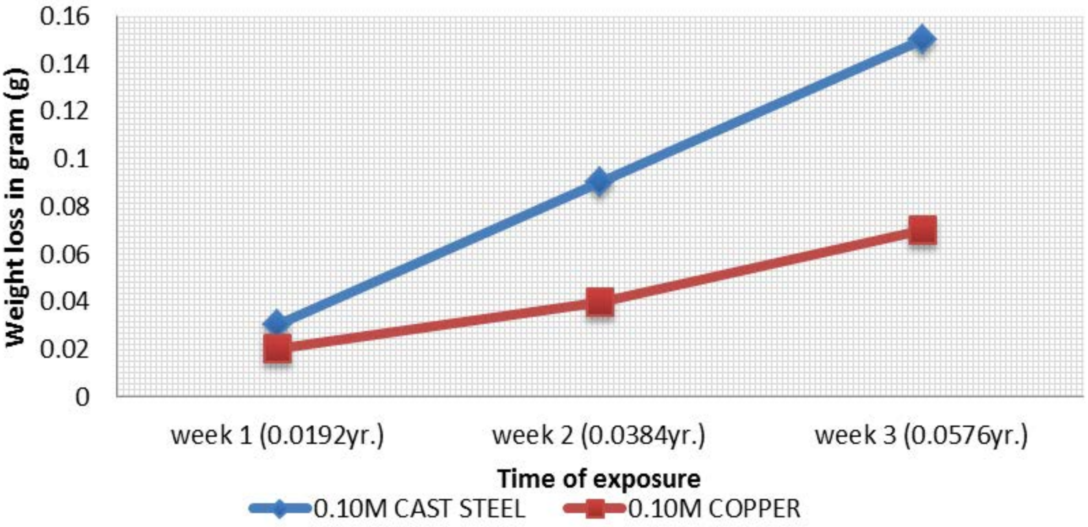

Figure 8. Weight Loss versus Exposure Time of Cast Steel and Copper in 0.1M of Sea Water

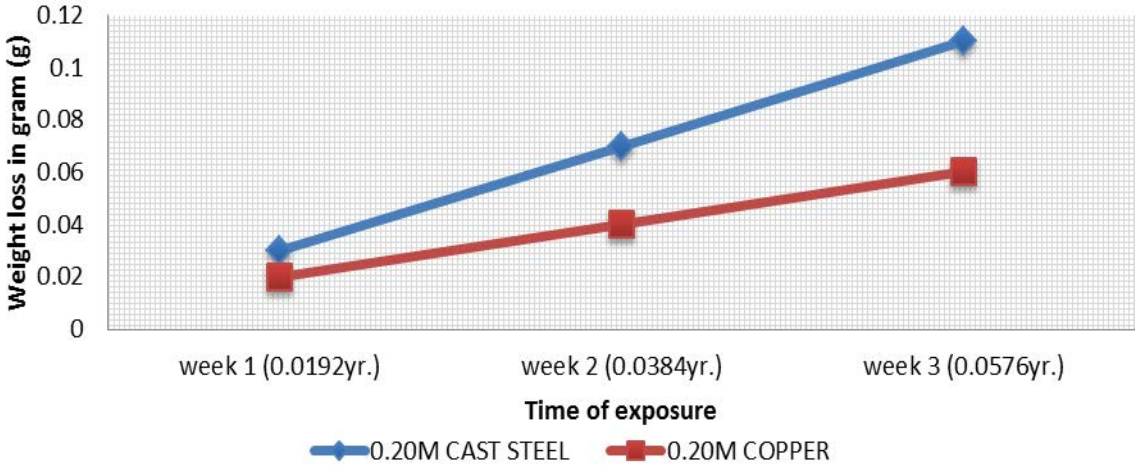

Figure 9. Weight Loss versus Exposure Time of Cast Steel and Copper in 0.000004M of Freshwater

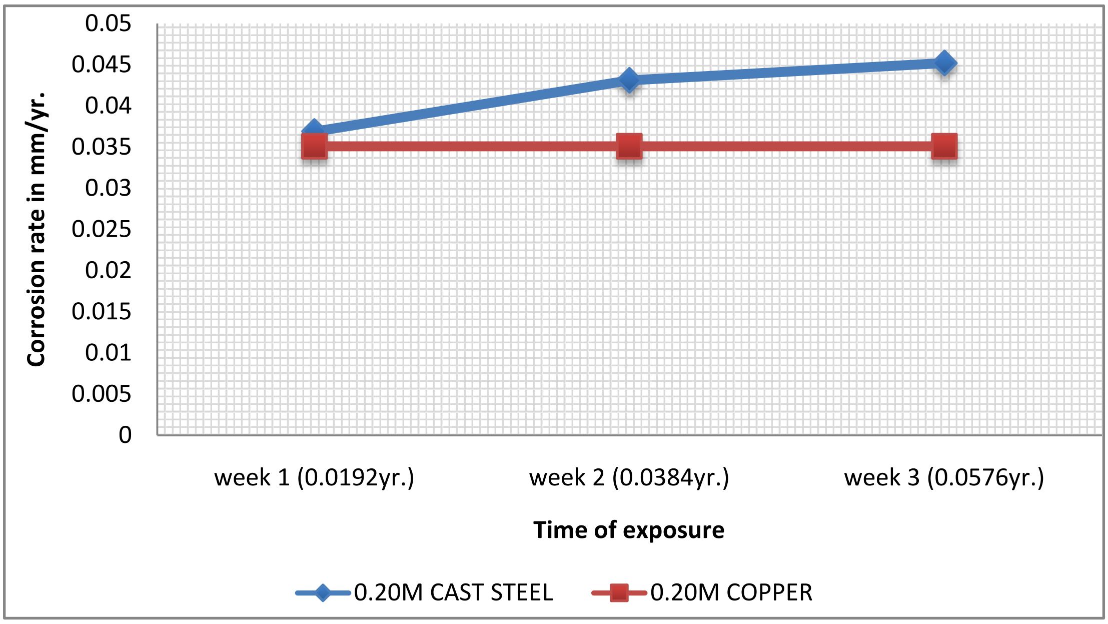

Figure 10. Corrosion Rate versus Exposure Time of Cast Steel and Copper in 0.20M of Seawater

Table 7. Hardness and Tensile Strength Testing Results for Steel and Copper Samples

	EQUIPMENT; MITECH 320 LEEB HARDNESS TESTER	Brinell Hardness Readings				TENSILE STRENGTH (MPa)			
S/N	Sample description	HB1	HB2	HB3	Average	σ_1	σ_2	σ_3	$\sigma_{Average}$
1	CAST STEEL BEFORE IMMERSION	118	129	95	114	433	418	391	414
2	CAST STEEL AFTER IMMERSION	143	116	96	118	451	475	395	440
3	COPPER BEFORE IMMERSION	168	167	153	163	789	771	768	776
4	COPPER AFTER IMMERSION	138	168	142	149	746	734	752	744

3.2. Hardness and Tensile Strength Test for Steel and Copper Samples

Table 7 shows that the hardness and the tensile strength of the cast steel increased after the immersion. This is seen as the average result increased from 114MPa to 118MPa for Hardness and 414MPa to 440MPa for the tensile strength of the cast steel. Also, copper decreased in hardness and tensile strength as the results obtained reduced from 163MPa – 149MPa and 776MPa – 744MPa for the hardness and tensile strength respectively. Consequently, comparing the results obtained for both specimens, it is evident that the hardness and tensile strength of the copper specimen before and after the immersion are higher than that of the cast steel.

3.3. Surface Analysis

The surface analysis of the specimens was carried out using the inverted metallurgical microscope giving a clearer view of the micro-structure of the specimens used before and after the 21days immersion. The micrographs for both specimens obtained from the inverted metallurgical microscope are shown in Figure 11 and Figure 12.

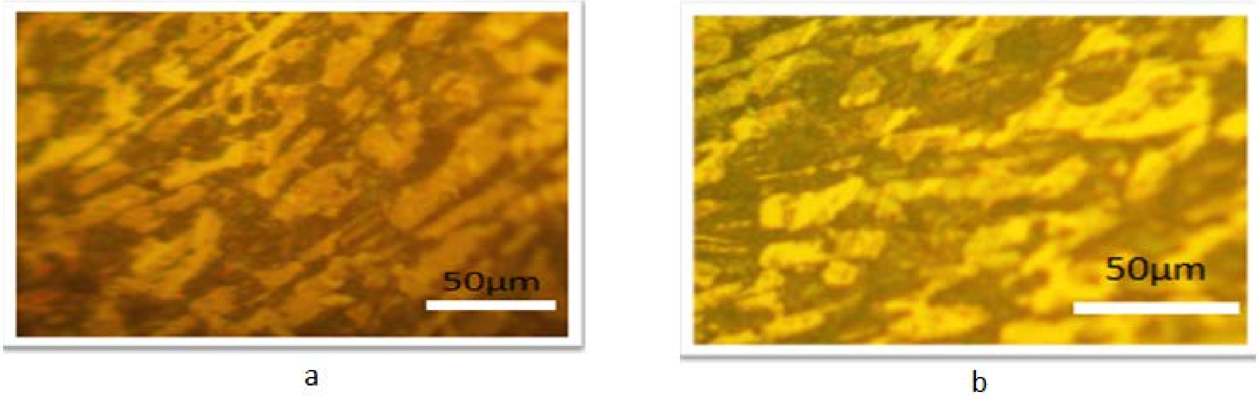

Figure 11. a: Micrographs of cast Steel before Immersion, b: Micrographs Cast Steel after Immersion

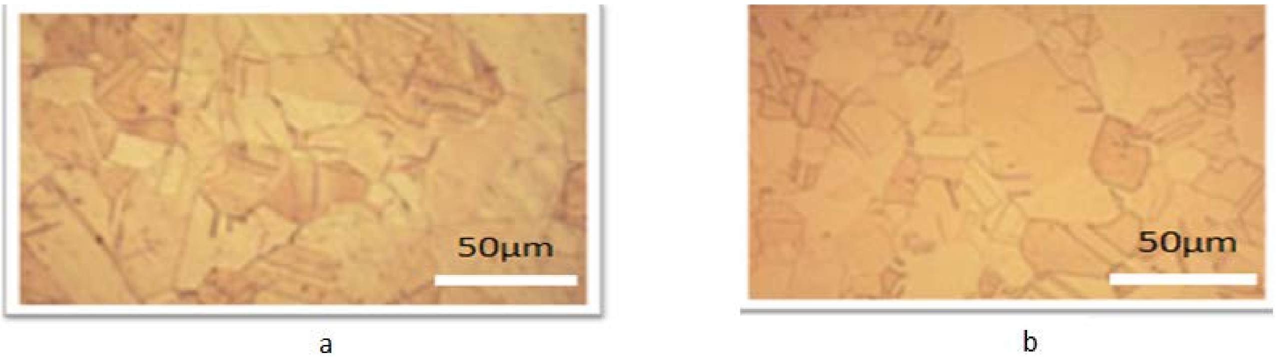

Figure 12. a: Micrographs of Copper before Immersion, 12b: Micrograph of Copper after Immersion

Figure 11a and Figure 11b showed the optical micrographs of the cast steel which revealed the morphology of the polished metals prior to immersion and after immersion in the 0.000004M fresh water concentration. Figure 12a and Figure 12b shows the optical micrographs of the copper specimen which revealed the morphology of the polished metals prior to immersion and after immersion in the 0.1M Sea water concentration respectively. The result obtained from micrographs for the cast steel specimen showed a rough and bumpy surface indicating general corrosion. The micrograph of the cast steel after immersion tends to be rougher than that of the micrograph before immersion. This can be attributed to the impact of corrosion on the microstructure after immersion for 21days in a 0.1M concentration of sea water. Similarly, the micrographs obtained for the copper specimen before and after immersion barely showed much difference which indicates limited corrosion impact on the specimen though the micro-surface appeared to be cracked. The cracks can be seen to be more spaced out for the after immersion than that of the before. This could be credited to the effect of corrosion on the microstructure after the 21 days of immersion in the 0.1M Sea water concentration. Therefore, comparing the micrographs of both specimens, it can be said that the effect of corrosion on the microstructure of the specimens is more intense on the cast steel specimen than it is on the copper specimen even though both showed indications of general corrosion.

4. Conclusion

This research has gone through a thorough examination and comparison of the rates of corrosion of cast steel and copper specimens at different salinity concentrations. The specimens were subjected to weight loss experiment, tensile and hardness strength of the specimens were also tested and the surfaces of both specimens, analyzed microscopically. The study revealed that cast iron corrodes faster in all the test environments with greater weight loss as compared to the copper specimen which experienced no weight loss or corrosion impact for the first and second week at 0.000004M concentration.

Also, the corrosion rate in 0.10M for the second week and 0.20M for the third week of seawater solution obtained for both cast steel and copper specimens showed tremendous effect of salinity on the rate of corrosion. Consequently, the gradual increase in weight loss of the cast steel specimen from 14.79g -14.63g, 13.40g - 13.25g and 15.61g - 15.51g for 0.000004M, 0.1M and 0.2M concentrations and from 1.960g - 1.950g, 1.920g - 1.850g and 1.970g - 1.910g for 0.000004M, 0.1M and 0.2M for the copper specimen confirmed the interdependence of exposure time and weight loss and this was demonstrated to further affirm the effect of the exposure time on both specimens in their various test media.

Recommendations

Based on the results obtained in this research, work the following recommendations were proffered:

1. Serious considerations should be given to material selection so as to ensure long term corrosion control.
2. All metals for the design of marine heat exchangers should be given proper attention with proper periodic monitoring and maintenance activities.

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