

# Fresh and Sea Water Immersion Corrosion Testing on Steel in Low Temperature

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## Abstract

The aim of the present study is to experimentally examine the corrosion progress characteristics of steel associated with fresh and sea water immersion at low temperatures. Three types of steel, namely mild steel (Grade A) and high tensile steel (Grades A and D) are tested under various corrosive conditions in the fresh water, in the sea water and in the air at a temperature of 18°C, 0°C and -10°C. Mass loss of test specimen due to corrosion is measured at a monthly interval and it is converted to a loss of steel plate thickness. Based on the test database, the effects of parameters affecting the corrosion progress are discussed. Test database obtained in the present study are documented.

**Key words:** Water Immersion Corrosion Testing; Corrosion Rate; Low Temperature; Ship Structural Steel; Corrosion Wastage

## 1. Introduction

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While steel is a comprehensively used in engineering structures, it is very vulnerable to the exposure of corrosive environments. Water immersion corrosion on steel must be associated with various factors such as oxygen content, carbon dioxide, salinity, pH value of water, carbonate solubility, temperature, atmospheric pressure, suspended solids, velocity of waves, chemical composition and surface roughness (Paik et al. 2003, 2004, Shifler 2004, Zayad et al. 2005, Little and Lee 2007, Paik and Melcher 2008, Guedes Soares et al. 2008).

A number of contributions to corrosion assessment and management have been made in the literature (Afanasief 1975, Schumacher 1959, Melcher and Ahammed 1996, Paik and Thayamballi 2007). As a proactive measure, surface coating is one of the effective methods to protect corrosion, as it prevents the corrosion based on coating life (ClassNK 1995, Rajput et al. 2018). Apart from the corrosion protection measures, it is very important to predict the corrosion wastage over time, and useful corrosion wastage models have been developed in the literature (Melcher 1997, 2003). A physical model of corrosion progress mechanism has been developed by Melcher (2008, 2011). Melcher (2003) has discussed the effects of environmental and material factors in submerged corrosion. Lin and Wang (2005) established the correlation between accelerated corrosion and atmospheric corrosion on soft steel (SPHC), carbon steel (SS400) and weathered steel (A588) with a maximum error of 31.6%. Various factors associated with the corrosion rate such as Cl ion deposition flux, time of wetness and temperature were taken into account to predict the progress of corrosion rate in real environment conditions.

Moreover, the progress of corrosion in the real environment is slow and it takes a long time to produce a response in steel structures. Efforts have been made to predict corrosion wastage as a function of time of oil well tubes in subsea conditions (Paik and Kim 2012, Mohd and Paik 2013).

To simulate the corrosion process in a laboratory environment, most studies have used various accelerated corrosion techniques (Almusallam 2001, Du et al. 2005, Apostolopoulos et al. 2006, 2007). Further, to produce natural effect of corrosion in the laboratory, Palsson and Mirza (2002) have used steel specimen collected from actual field conditions, for instance corroded steel bridges. Kim et al. (2017) studied the effect of corrosion damage on the tensile behavior of 75-year-old painted steel bridges exposed to the marine environment. The remaining thickness of specimens was obtained through an optical 3D digitizing system, and the study evaluated the mechanical properties of the steel specimens.

Chernov et al. (2018) reported observations related to corrosion progress in ship structural steel exposed to Sub-Arctic water as well as temperate water, and compared the corrosion behaviour. Melcher (1997, 2008, 2011) reported the field data which is very informative to understand the effect of corrosion on various marine applications and also to predict the corrosion rate through proposed corrosion wastage models. Further, Guedes Soares and Garbatov (1998, 1999, 2010) proposed a corrosion wastage model for reliability assessment associated with structural maintenance.

It is however obvious that naturally progressed corrosion can reflect better field conditions relative to progressed corrosion in the laboratory. Hence, the present study has also examined the

progress of corrosion in natural environments associated with sea water immersion. It builds the understanding of the progress of corrosion in various types of ship structural steel in realistic conditions. The acceleration methods of corrosion are not used, but rather a natural method over time was adopted to observe the progress of corrosion in terms of mass loss per month in different steel specimens. Corrosion database is developed using tensile coupon test specimens to identify the effects of corrosion on material properties which will be reported in a separate article.

## **2. Experimental Procedure**

### **2.1 Test Specimen**

Figure 1 shows specimens used for corrosion testing in the laboratory which are tensile coupon test specimens to be used for identifying mechanical properties of material. The specimens were extracted on the basis of their rolling direction from the parent plate sheet. The gauge length of the specimens was 60 mm and the thickness was 6 mm. The reason why the tensile coupon test specimens are used is that they will be used to examine the effects of corrosion on the material properties which will be reported in a separate article. A total of eighteen steel specimens of mild steel (Grade A) and high tensile steel (AH-32 and DH-32) are used to observe corrosion progress characteristics associated with parameters of influence such as temperature, immersion in fresh or sea water as well as in the air.

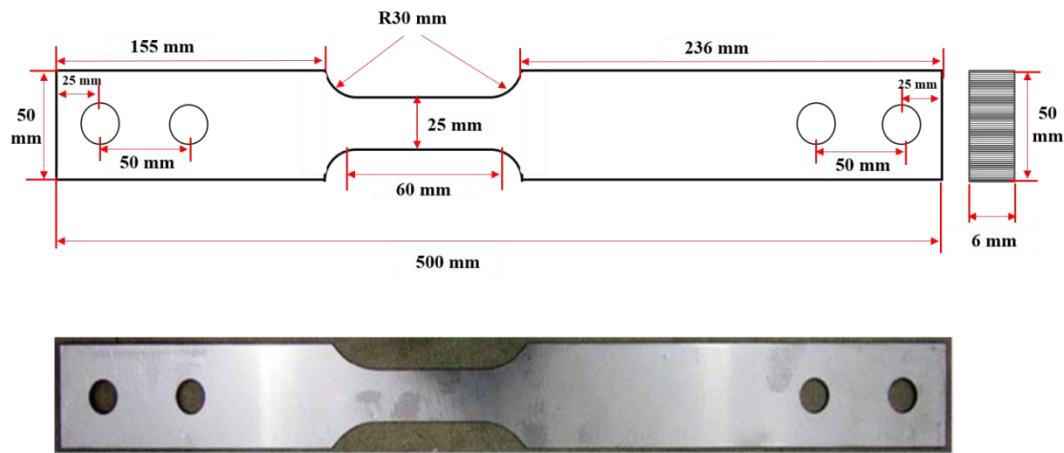


Figure 1. Geometry of tensile coupon test specimen

## 2.2 Test Method

The mass of each specimen was approximately 1 kilogram, and their sizes and shapes were identical to allow a direct comparison of mass loss characteristics over time. Two specimens from each steel grade were kept in the sea water, in the fresh water and in the air at different temperatures (18°C, 0°C and -10°C). The specimens were either kept in submerged conditions with 3000 ml seawater or freshwater, or were kept dry in the air.

In the period of year, the temperature profile of water may vary significantly, and eventually microbiological conditions of the water could also change. Therefore, in the present experimental study, the seawater was regularly replaced in the interval of every week time to maintain natural sea water conditions. The seawater was taken from the seashore at Yongho-dong, Busan city in South Korea. Salinity was measured using a salinity meter, but the dissolved oxygen was obtained through the DO meter. The average value of salinity was approximately 2.6% for seawater, and 1.05% for fresh water, see Table 1.

Table 1. Environmental conditions of water used in present study.

| Water condition | Salinity (%) |             | Dissolved Oxygen (mg/l) |             | Raw water temperature (°C) |             | Water temperature in laboratory (°C) |             |
|-----------------|--------------|-------------|-------------------------|-------------|----------------------------|-------------|--------------------------------------|-------------|
|                 | Sea-water    | Fresh water | Sea-water               | Fresh water | Sea-water                  | Fresh water | Sea-water                            | Fresh water |
| Largest         | 3.1          | 1.4         | 11.3                    | 14.0        | 26                         | 36          | 18, 0, -10                           | 18, 0, -10  |
| Smallest        | 2.1          | 0.7         | 6.7                     | 7.8         | 6                          | 10          | 18, 0, -10                           | 18, 0, -10  |
| Average         | 2.6          | 1.05        | 9.0                     | 10.8        | 16                         | 23          | 18, 0, -10                           | 18, 0, -10  |

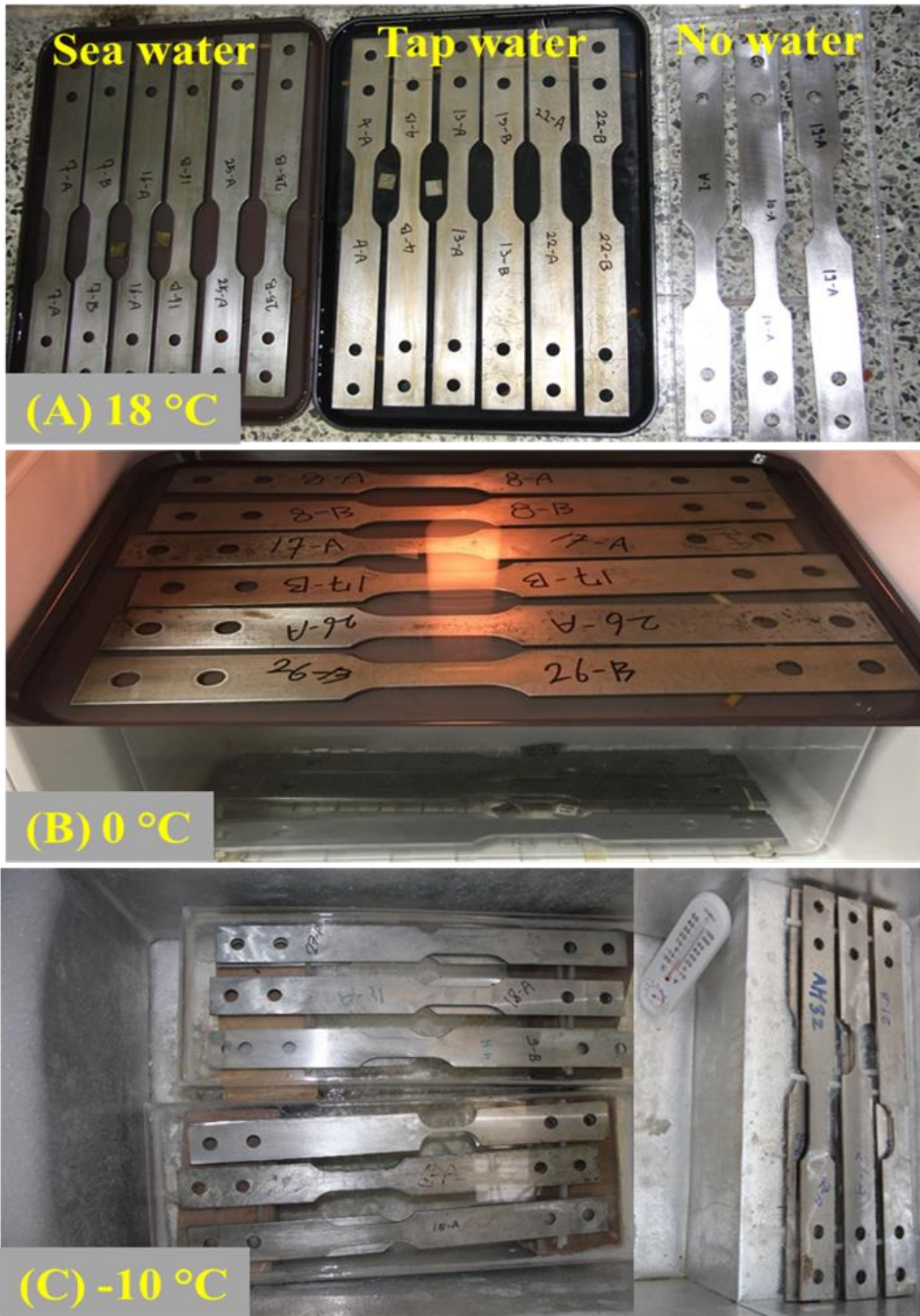


Figure 2. Test specimens submerged in sea water, in fresh water and in the air at (a) 18°C (b) 0°C and (c) -10°C

## 2.1 Corrosion measurement

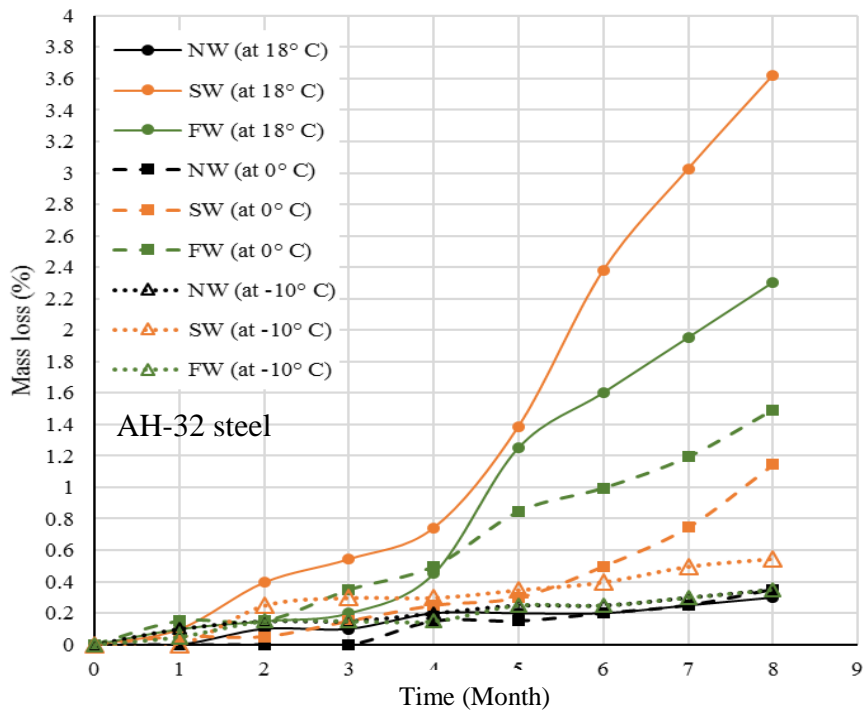
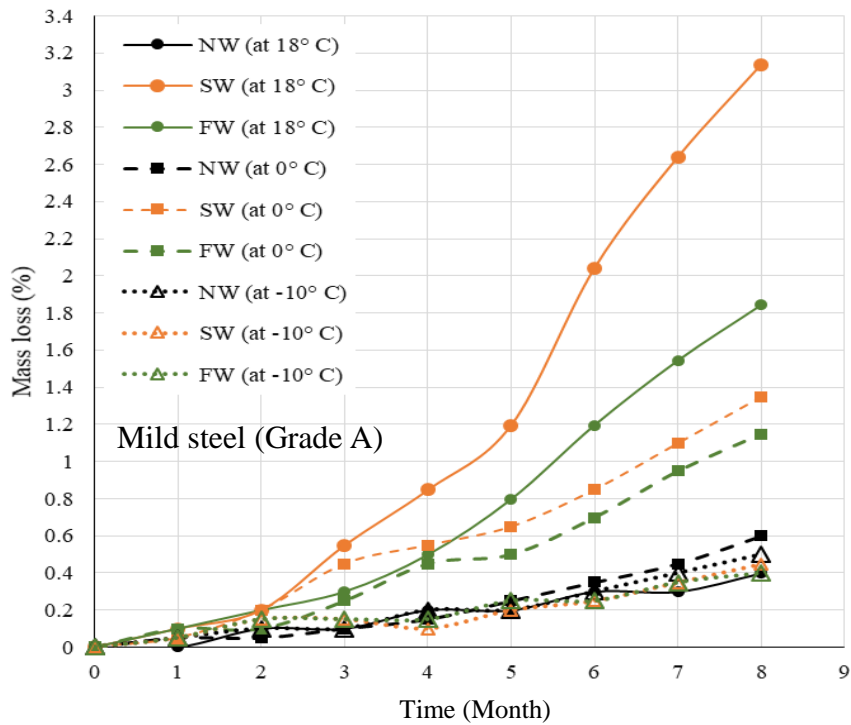
Prior to the experiment, each test specimen was abraded using coarse and fine mesh sandpaper and then rinsed with distilled water. The mass of the intact specimens was measured and the specimens were then placed in sea water, in fresh water and in the air at 18°C, 0°C and -10°C. Corrosion was allowed to develop for a month (30 to 40 days) in each condition. Thereafter, the accumulated corrosion (rust) was cleaned off from the surface of the specimens. The rusting was removed attentively from the surface, and cleaning was also carefully performed with the help of coarse and fine meshed sandpapers. The mass of each specimen was measured in the interval of every month (30-40 days) with the help of weighing machine of 1-gram precision. The measured mass loss was converted to a loss of thickness (in millimeter) per unit area of the specimen.

To obtain more accurate data, the average masses of pairs of specimens kept in similar conditions were calculated. The average mass calculated in each condition during every month is presented in Table 2. The above-mentioned experimental process was continued for several months to obtain data on corrosion progress. To plot a graphical model, corrosion was measured in terms of the percentage of average mass loss of the specimens at a monthly interval. The corrosion progress rates of various types of steel were plotted as the mass loss percentage over time, as shown in Fig. 3. It is found from Fig.3 that the corrosion progression is slower at colder temperature.



Table 2. Average mass loss of test specimens over time.

| Time (Month) | Mild steel (Grade A) at 18°C |           |             | Mild steel (Grade A) at 0°C |           |             | Mild steel (Grade A) at -10°C |           |             |
|--------------|------------------------------|-----------|-------------|-----------------------------|-----------|-------------|-------------------------------|-----------|-------------|
|              | Air                          | Sea water | Fresh water | Air                         | Sea water | Fresh water | Air                           | Sea water | Fresh water |
| 0            | 1008                         | 1003.5    | 1003.5      | 1002                        | 1002      | 1002.5      | 1003.5                        | 1006.5    | 1004.5      |
| 1            | 1008                         | 1002.5    | 1002.5      | 1001.5                      | 1001.5    | 1001.5      | 1003                          | 1006      | 1004        |
| 2            | 1007                         | 1001.5    | 1001.5      | 1001.5                      | 1000      | 1001.5      | 1002.5                        | 1005      | 1003        |
| 3            | 1007                         | 998       | 1000.5      | 1001                        | 997.5     | 1000        | 1002.5                        | 1005      | 1003        |
| 4            | 1006                         | 995       | 998.5       | 1000.5                      | 996.5     | 998         | 1001.5                        | 1005.5    | 1003        |
| 5            | 1006                         | 991.5     | 995.5       | 999.5                       | 995.5     | 997.5       | 1001.5                        | 1004.5    | 1002        |
| 6            | 1005                         | 983       | 991.5       | 998.5                       | 993.5     | 995.5       | 1000.5                        | 1004      | 1002        |
| 7            | 1005                         | 977       | 988         | 997.5                       | 991       | 993         | 999.5                         | 1003      | 1001        |
| 8            | 1004                         | 972       | 985         | 996                         | 988.5     | 991         | 998.5                         | 1002      | 1000.5      |
| Time (Month) | Steel (AH-36) at 18°C        |           |             | Steel (AH-36) at 0°C        |           |             | Steel (AH-36) at -10°C        |           |             |
|              | Air                          | Sea water | Fresh water | Air                         | Sea water | Fresh water | Air                           | Sea water | Fresh water |
| 0            | 1008                         | 1008.5    | 999.5       | 1001.5                      | 1003.5    | 1006        | 1005.5                        | 1007      | 1008        |
| 1            | 1008                         | 1007.5    | 998.5       | 1001.5                      | 1003      | 1004.5      | 1004.5                        | 1007      | 1007.5      |
| 2            | 1007                         | 1004.5    | 998         | 1001.5                      | 1003      | 1004.5      | 1004                          | 1004.5    | 1006.5      |
| 3            | 1007                         | 1003      | 997.5       | 1001.5                      | 1002      | 1002.5      | 1004                          | 1004      | 1006.5      |
| 4            | 1006                         | 1001      | 995         | 1000                        | 1001      | 1001        | 1003.5                        | 1004      | 1006.5      |
| 5            | 1006                         | 994.5     | 987         | 1000                        | 1000.5    | 997.5       | 1003                          | 1003.5    | 1005.5      |
| 6            | 1006                         | 984.5     | 983.5       | 999.5                       | 998.5     | 996         | 1003                          | 1003      | 1005.5      |
| 7            | 1005.5                       | 978       | 980         | 999                         | 996       | 994         | 1002.5                        | 1002      | 1005        |
| 8            | 1005                         | 972       | 976         | 998                         | 992       | 991         | 1002                          | 1001.5    | 1004.5      |
| Time (Month) | Steel (DH-32) at 18°C        |           |             | Steel (DH-32) at 0°C        |           |             | Steel (DH-32) at -10°C        |           |             |
|              | Air                          | Sea water | Fresh water | Air                         | Sea water | Fresh water | Air                           | Sea water | Fresh water |
| 0            | 998                          | 997       | 999         | 992                         | 998.5     | 998.5       | 1044                          | 1044      | 998         |
| 1            | 998                          | 995.5     | 998         | 992                         | 997.5     | 996         | 1044                          | 1043.5    | 997.5       |
| 2            | 998                          | 993       | 997         | 992                         | 997       | 996         | 1042.5                        | 1043      | 997         |
| 3            | 998                          | 991       | 995.5       | 991                         | 995       | 995         | 1042.5                        | 1042.5    | 997         |
| 4            | 998                          | 989       | 994.5       | 991                         | 993       | 994         | 1042                          | 1040      | 996         |
| 5            | 997                          | 983.5     | 991.5       | 990                         | 991.5     | 991.5       | 1041.5                        | 1038      | 996         |
| 6            | 997                          | 973.5     | 987         | 989.5                       | 990.5     | 988.5       | 1041.5                        | 1035      | 995         |
| 7            | 996.5                        | 967       | 984         | 988.5                       | 989.5     | 986         | 1041                          | 1032.5    | 994.5       |
| 8            | 996.5                        | 961       | 980.5       | 987.5                       | 988       | 982.5       | 1040.5                        | 1029      | 994         |



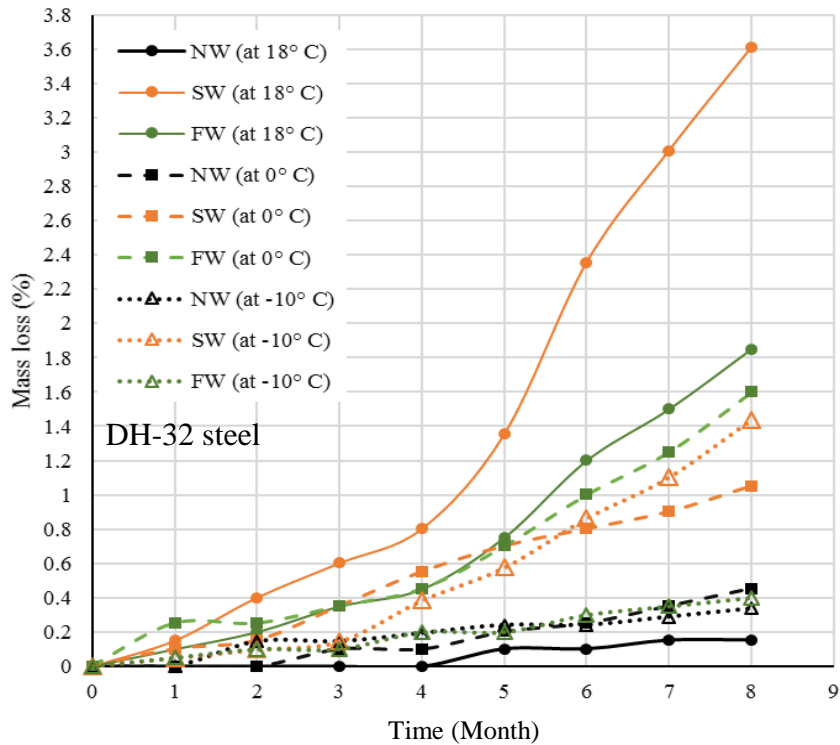


Figure 3. Mass loss with passing age of steel specimens submerged in sea water (SW), fresh water (FW), and in the air or no water (NW) conditions at different temperatures: (a) Mild steel (Grade A) (b) AH-32 steel and (C) DH-32 steel.

## 2.2 Effects of various environmental conditions

The progress of corrosion is influenced by various environmental factors, and is thus a complex problem. The authors assessed the corrosion rates of three different types of ship structural steel (Grade A, AH-32 and DH-32) in conjunction with parameters such as temperature, salinity and time. Salinity was 2.6% and 1.05% for seawater and fresh water respectively.

In open sea submerged exposure conditions, temperature varies across space and time. Therefore, this paper considered three different temperatures to try to replicate the real environmental temperature conditions of sea water, although it is extremely challenging to recreate the exact temperature conditions of the open sea environment. Corrosion progress in the specimens was strongly associated with temperature variation in the sea water, fresh water and no water conditions. The corrosion rate increased as temperature increased. The fastest corrosion rate occurred in the sea submerged condition at room temperature (18°C), followed by the fresh water and no water conditions. At relatively low temperatures (0°C and -10°C), the corrosion rate decreased. The corrosion rate for all three types of ship structural steel was also related to

water salinity. Mass loss in relation to temperature for various steel specimens are plotted in Fig. 4-6. AH-32 and DH-32 steel had the highest corrosion rate in the sea submerged condition (2.5% salinity), as shown in Fig. 4(a). Mild steel had a slower corrosion rate. A detailed comparison of eight-month data is provided below.

(a) At room temperature (18°C)

1. In the sea submerged condition, the AH-32 steel specimen displayed the highest corrosion, followed by DH-32 and mild steel grade A. The percentages of average mass loss due to corrosion after eight months were 3.60%, 3.62% and 3.13% for DH-32, AH-32 and mild steel respectively.
2. In the fresh water submerged condition, DH-32 and mild steel displayed almost the same level of corrosion, with an average mass loss of 1.85% and 1.84% respectively. AH-32 steel displayed a mass loss of 2.3%.
3. In dry conditions (without water), mild steel displayed the highest mass loss, followed by AH-32 and DH-32 steel (0.39%, 0.29% and 0.15% respectively).

(b) At low temperature (0°C)

1. In sea submerged conditions mild steel (grade A) displayed a mass loss of 1.34%, followed by AH-32 (1.14%) and DH-32 (1%).
2. In fresh water submerged conditions the mass loss for mild steel was 1.14%. AH-32 displayed 1.49% mass loss, and DH-32 loss was 1.6%. It should be noted that the mass loss for AH-32 and DH-32 steel was almost equal.
3. In the no water condition, the maximum mass loss occurred in mild steel (0.59%), followed by DH-32 steel (0.45%) and AH-32 steel (0.34%).

(c) At very low temperature (-10°C)

1. In the sea submerged condition, DH-32 displayed 1.43% mass loss, followed by AH-32 (0.54%) and mild steel (0.45%).
2. In fresh water submerged conditions mild steel mass loss was 0.39%, AH-32 was 0.34% and DH-32 was 0.40%, and was thus almost identical.
3. In the no water condition, the maximum mass loss occurred in mild steel 0.49%, followed by AH-32 steel (0.35%) and DH-32 steel (0.33%).

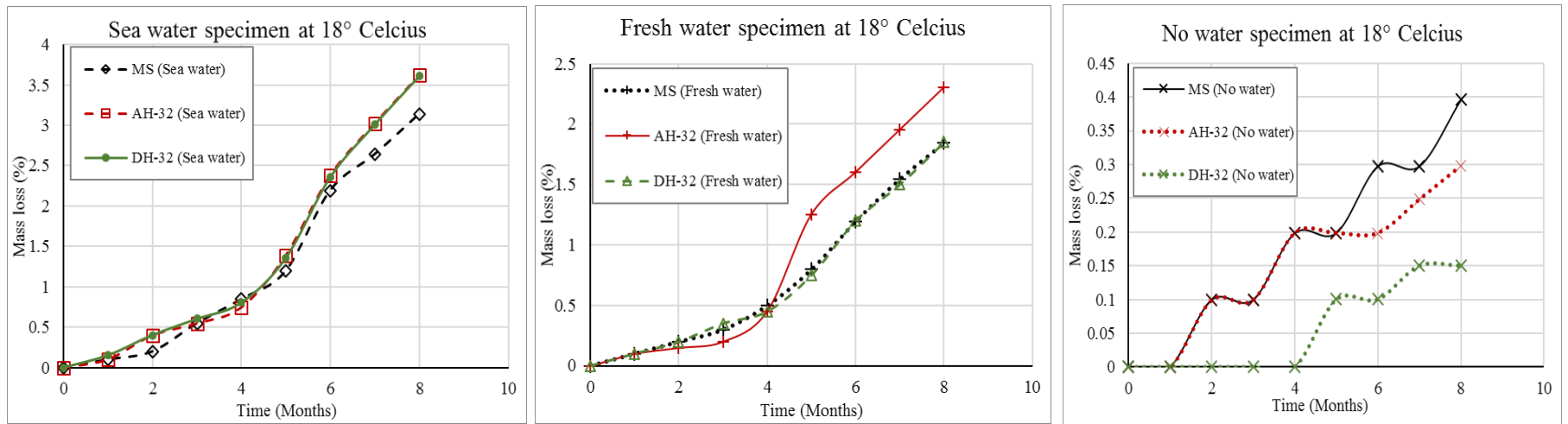


Figure 4. Mass loss of various steel specimens at room temperature (18°C) in (a) Sea submerged (b) Fresh water submerged and (c) No water conditions

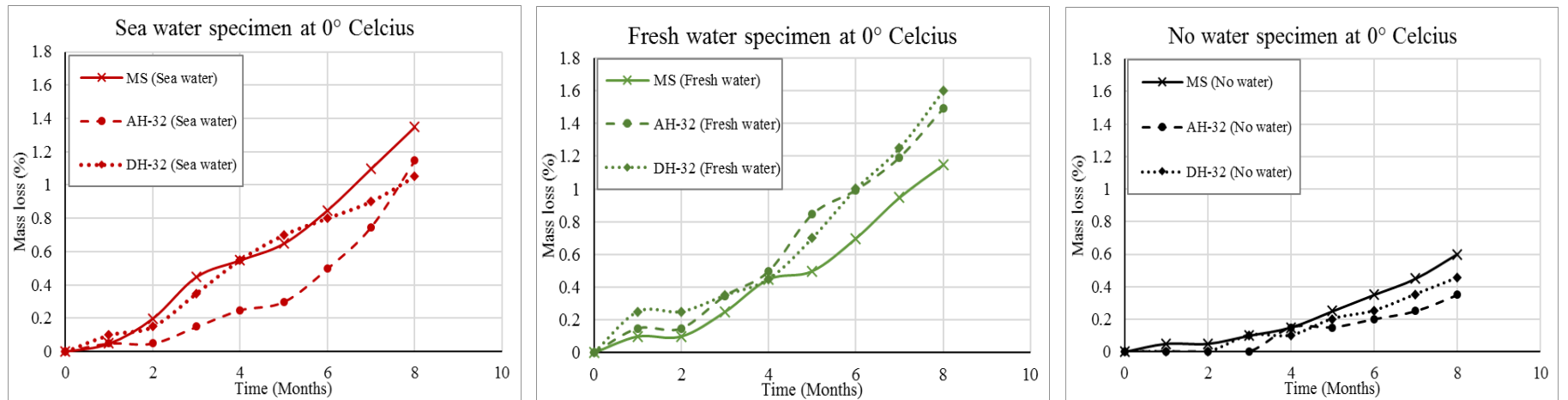


Figure 5. Mass loss of various steel specimens at room temperature (0°C) in (a) Sea submerged (b) Fresh water submerged and (c) No water conditions

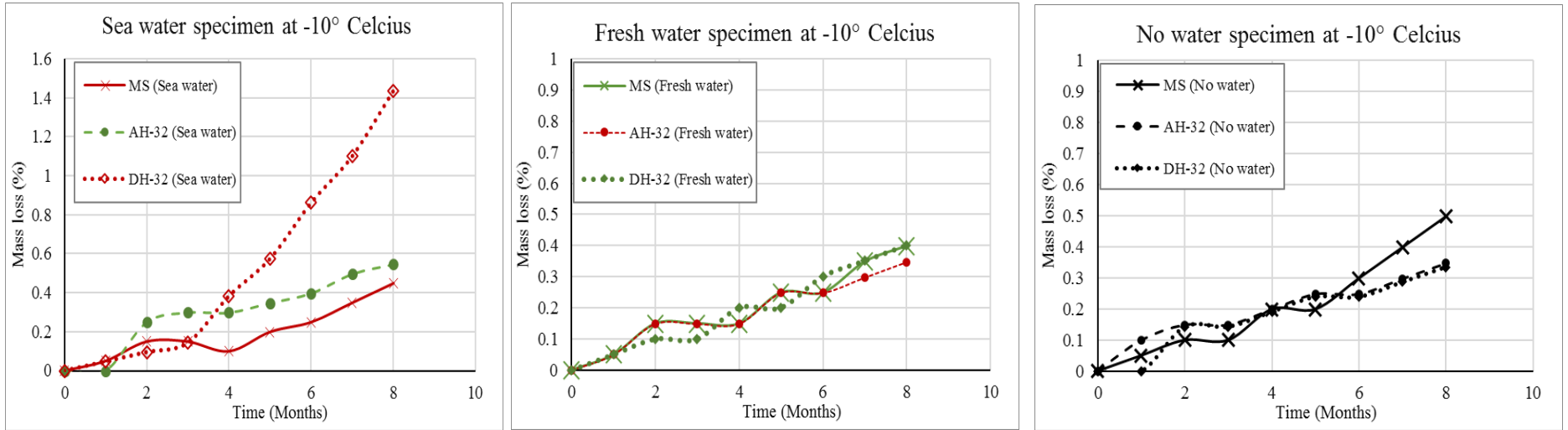


Figure 6. Mass loss in various steel specimens at room temperature (-10°C) in (a) Sea submerged (b) Fresh water submerged and (c) No water conditions

### 3 Mathematical estimation of corrosion

Firstly, the obtained average mass loss of specimens through corrosion experiments was converted in to the thickness loss per unit area. Further, to understand the behavior of corrosion wastage based upon the experimental data a second order quadratic polynomial was solved to predict thickness loss per unit area (equation 1). The polynomial equation was solved by using three environmental conditions as input variables (surrounding temperature, salinity of water and time) and thickness loss as output data. The polynomial equation has total number of ten constants that could be calculated as  $A = \frac{(n+1)(n+2)}{2}$ . Where, n represents the number of variables hence total ten number constants need to be find for predicting the corrosion wastage of the specimens as a function of salinity, temperature and time.

$$y = a_0 + \sum_{i=1}^n b_i x_i + \sum \sum_{i < j} c_{ij} x_i x_j + \sum_{i=1}^n d_i x_i^2 \quad (1)$$

In the equation 1,  $y$  represents the thickness loss millimeter, and  $a_0$ ,  $b_i$ ,  $c_{ij}$ , and  $d_i$  are the constants, and  $x_i$  represents the variables temperature ( $x_1$ ), time ( $x_2$ ) and salinity( $x_3$ ).

The required ten constants were then obtained for each material used in the present study by solving the polynomial through Maple software. The available nonlinear fit module in Maple software was used to calculate the polynomial coefficients, which is based on the minimization of the least-squares error. The constants for each material are presented in Table 3.

The accuracy of the mathematical model was checked by calculating the mean error as follows.

$$\text{Mean Error} = \frac{1}{m} \sum_{i=1}^n |y_e - y_p| \quad (2)$$

Where  $m$  is total number of data points,  $y_e$  is the experimental value, and  $y_p$  is the predicted value. The accuracy of the predicted corrosion rate was also measured by comparing it with the straight-line plot in Figure. 10. The mean error between experimental and predicted values of

corrosion wastage was calculated  $3.616 \times 10^{-5}$  for mild steel,  $4.412 \times 10^{-5}$  for AH-32 steel and  $9.436 \times 10^{-6}$  for DH-32 respectively. The experimental data points are compared with those of predicted values, see Figures 7-9 for mild, AH-32 and DH-32 steel respectively. The predictions were closely found in agreement for the sea submerged condition, followed by the fresh water and without water conditions. However, the mathematical model spectacles variation in wastage of corrosion for relatively small period of time.

Table 3. Coefficients values obtained by solving the polynomial

| Mild steel (Grade A) |           |          | AH-32 steel |         | DH-32 steel |         |
|----------------------|-----------|----------|-------------|---------|-------------|---------|
| S. No.               | Constants | Value    | Constants   | Value   | Constants   | Value   |
| 1                    | $a_0$     | 0.0084   | $a_0$       | 0.0037  | $a_0$       | 0.0075  |
| 2                    | $b_1$     | -0.0014  | $b_1$       | -0.0020 | $b_1$       | -0.0014 |
| 3                    | $b_2$     | -0.0029  | $b_2$       | -0.0040 | $b_2$       | -0.0050 |
| 4                    | $b_3$     | 0.0021   | $b_3$       | 0.0133  | $b_3$       | 0.0040  |
| 5                    | $d_1$     | -0.00001 | $d_1$       | 0.0000  | $d_1$       | 0.0000  |
| 6                    | $d_2$     | 0.0008   | $d_2$       | 0.0008  | $d_2$       | 0.0009  |
| 7                    | $d_3$     | -0.0029  | $d_3$       | -0.0077 | $d_3$       | -0.0042 |
| 8                    | $c_{12}$  | 0.0004   | $c_{12}$    | 0.0005  | $c_{12}$    | 0.0003  |
| 9                    | $c_{13}$  | 0.0008   | $c_{13}$    | 0.0009  | $c_{13}$    | 0.0008  |
| 10                   | $c_{23}$  | 0.0034   | $c_{23}$    | 0.0041  | $c_{23}$    | 0.0051  |



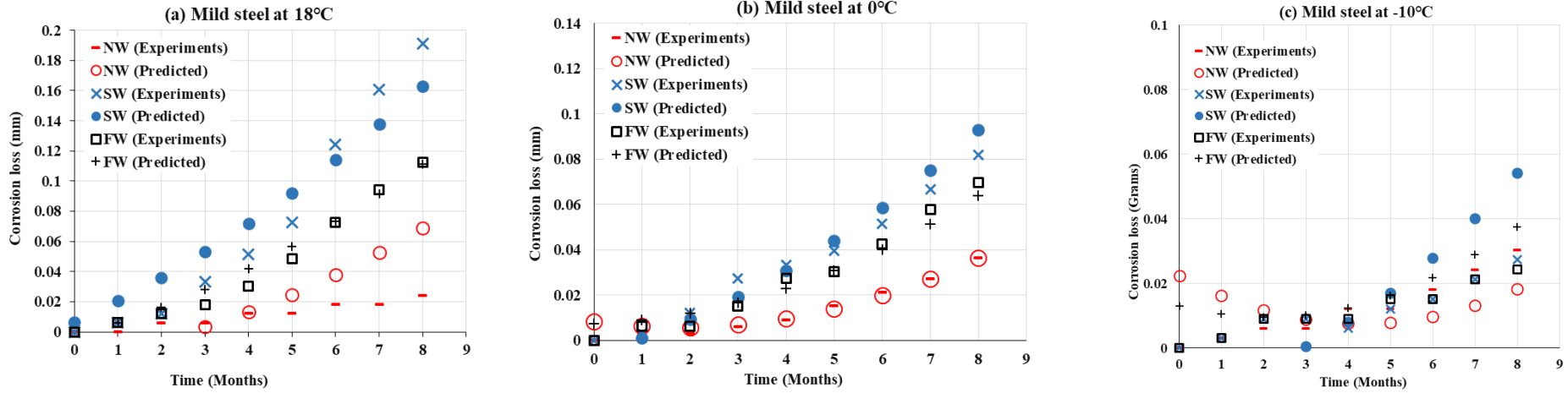


Figure 7. Comparison of experimental and predicted thickness loss of mild steel in sea (SW), fresh (FW) and no water (NW) conditions at (a) 18°C temperature, (b) 0°C temperature and (c) -10°C temperature.

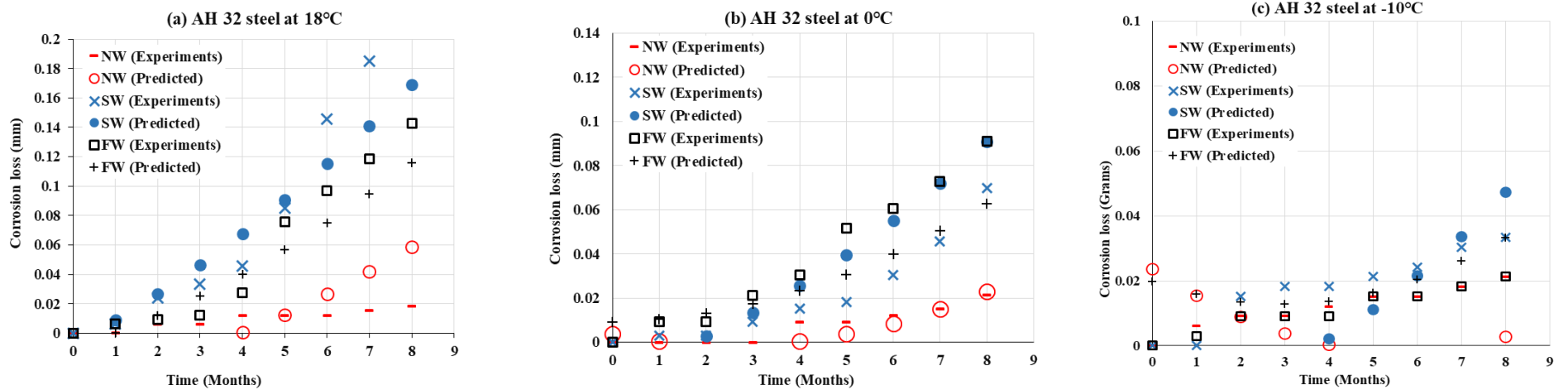


Figure 8. Comparison of experimental and predicted thickness loss of AH-32 steel in sea (SW), fresh (FW) and no water (NW) conditions at (a) 18°C temperature, (b) 0°C temperature and (c) -10°C temperature.

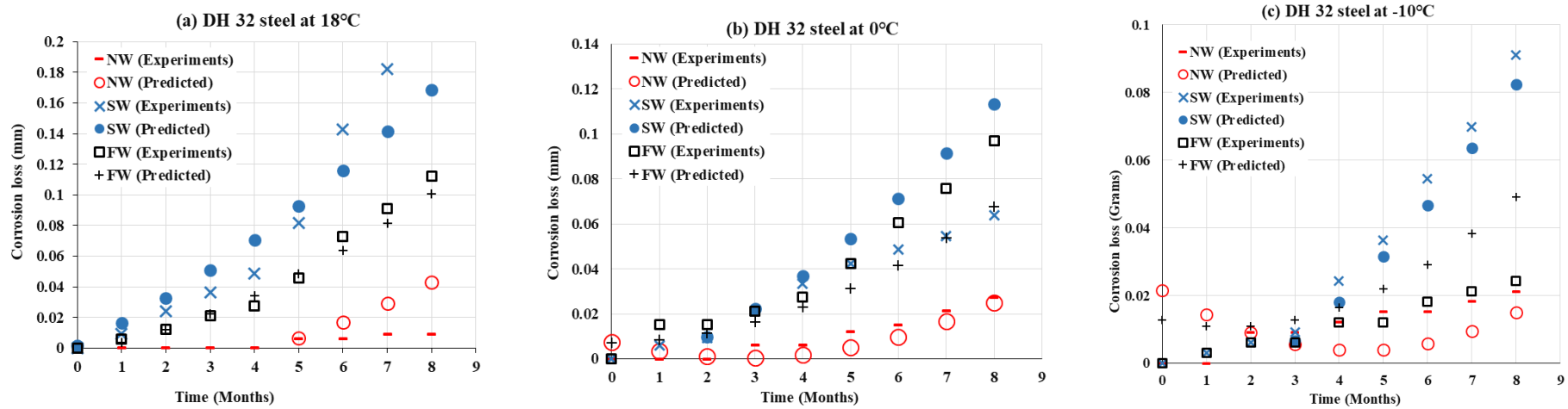


Figure 9. Comparison of experimental and predicted thickness loss of DH-32 steel in sea (SW), fresh (FW) and no water (NW) conditions at (a) 18°C temperature, (b) 0°C temperature and (c) -10°C temperature.

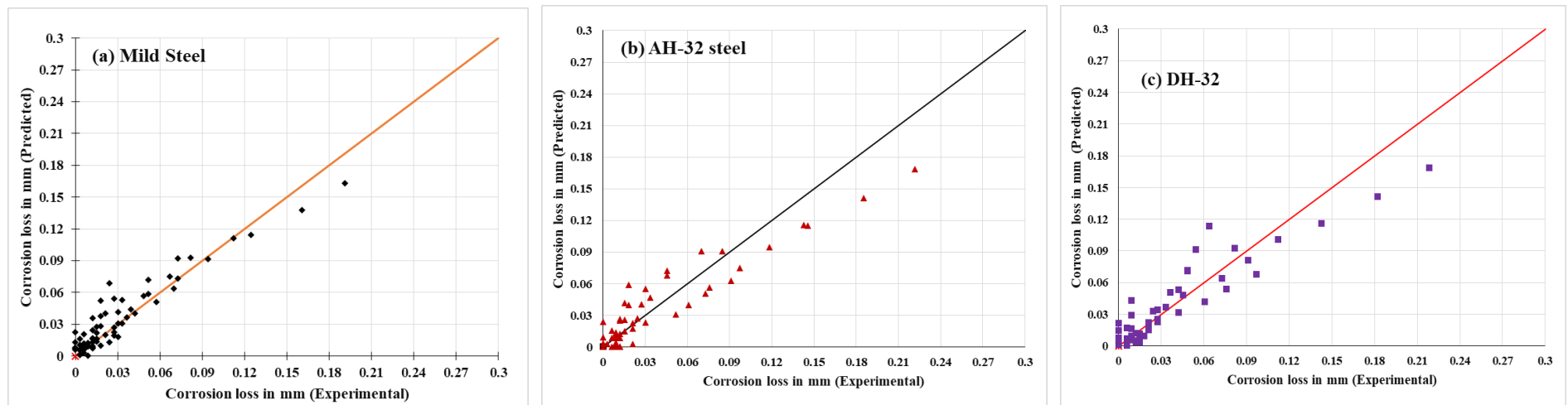


Figure 10. Experimental versus Predicted value for (a) mild steel, (b) AH-32 steel and (c) DH-32 steel

#### 4. Conclusion

The present experimental study scrutinized the corrosion progress rates in three types of ship structural steel (Grade A, AH-32 and DH-32) were kept fully immersed in sea water (SW), fresh water (FW) or no water (NW) at three different temperatures (18°C, 0°C and -10°C). The corrosion wastage was measured in terms of mass loss in the specimen and eventually converted in thickness loss per unit area.

Among all the three conditions studied, the maximum corrosion progress rate occurred in the sea submerged condition at room temperature (18°C). The slowest corrosion rate occurred in the no water or dry condition at -10°C. The mass loss was found to be increased with escalation of temperature. The AH-32 steel specimens immersed in sea water displayed the fast increase in corrosion rates (0.54%, 1.14% and 3.62% at -10°C, 0°C and 18°C respectively) with increase in temperature. The mass loss for DH-32 were 1.43%, 1.05% and 3.61%, and for mild steel the corrosion rates were 0.44%, 1.34% and 3.13% at -10°C, 0°C and 18°C correspondingly.

A second order polynomial was used to represent corrosion thickness loss as a function of three variables (temperature, salinity and time). For each type of steel, ten constants were obtained by solving polynomial mathematical equation to predict the corrosion wastage of specimens occurred due to corrosion. The mathematical equation closely fits with the corrosion thickness loss values obtained for sea submerged conditions followed by fresh water and no water conditions. Moreover, the corrosion is highly dependent process on several environmental conditions and age. However, the present polynomial has derived based on few environmental variables and relatively short period of time. Hence the present polynomial could not be capable enough to predict long term corrosion wastage closely.

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