Effects of Naturally-Progressed Corrosion on the Chemical and Mechanical Properties of Structural Steels

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Abstract

The objective of the paper was to experimentally examine the effects of corrosion wear on the chemical and mechanical properties of structural steels. Naturally-progressed corrosion testing on structural steel specimens was conducted during a period of 12 months. Three types of structural steels were tested: mild steel (grade A), AH32 steel, and DH32 steel. Different conditions of the corrosive environment were applied with three dry or water-immersed conditions, namely air (dry), freshwater immersion and seawater immersion, and with three temperatures, namely room temperature (18^{o}C), 0^{o}C, and -10^{o}C. The chemical and mechanical properties of structural steels were measured before and after the corrosion testing. Based on the test results, the characteristics of corrosion progression rate for structural steels were studied and reported in a separate paper [21, doi: 10.1080/17445302.2019.1664128]. This paper focused on how corrosion affects the chemical and mechanical properties of structural steels. Details of the test database were documented.

Keywords: Naturally-progressed corrosion, structural steel, mechanical properties, chemical properties, freshwater immersion corrosion, seawater immersion corrosion, low temperatures

1. Introduction

Steel is a common material used for the construction of naval, offshore, mechanical, and civil engineering structures. As steel structures get older, their safety and integrity can suffer from corrosion wear which is affected by various parameters of influence in the corrosive environment, including oxygen content, salinity, pH value of water, temperature, atmospheric pressure, suspended solids, velocity of water waves, together with various physical and chemical factors of material [1-5]. Land-based steel structures may be exposed to the immersion of freshwaters or related humidity while the surfaces of steel ship and offshore structures at sea are usually touched on seawaters [6]. In winter season or Arctic area, the operational temperature of such structures is in sub-zero temperatures (or lower than the room temperature).

To evaluate the structural integrity with corrosion damage at the level of steel structural members or entire structures, it is essential to identify the chemical and mechanical properties of corroded structural steels, i.e., at the level of materials. It is generally considered that corrosion does not affect the chemical and mechanical properties of structural steels [3], but obvious evidences or test database are lacking in the literature and thus some studies attempted to derive computational models that the corrosion wear was dealt with as a parameter of influence on the mechanical properties of structural steels [7-11]. The objective of this paper was to obtain the physical test database to investigate the effects of corrosion wear on the chemical and mechanical properties of structural steels, and ultimately to contribute to the prevention of such an unnecessary confusion on the issue.

The progression of corrosion with time depends on the corrosive environment and it is usually not very fast by nature taking several months or years. Structural steels with coating on surface do not commence corrosion until coating fails [12-14]. The corrosion progression characteristics are obviously probabilistic and random with not only time but also various sources of uncertainties, as found from pioneering works of the Paik's group with probabilistic models to predict corrosion wastage in terms of both time and probability density distributions [15-17].

Physical tests on corrosion of structural steels have been conducted at an artificial condition of the corrosive environment that could accelerate the corrosion progress and produced a desired quantity of corrosion in the laboratory [18-21]. These approaches were able to save testing time and enhanced the work efficiency during the corrosion progress. Other corrosion test studies are available with the corrosion conditions which are similar to actual fields of operation [22,23]. Most corrosion test studies in the literature have been focused on how the corrosion progresses and what the corrosion rate is [1], but the related studies on both the chemical and mechanical properties of structural steels are not found in the literature.

In this paper, corrosion tests on the specimens of mild steel (grade A), AH32 steel, and DH32 steel were conducted for a period of 12 months. The shape and geometry of test specimens were exactly the same as for the coupons which were used for tensile testing to examine the mechanical properties of steel. The specimens for the chemical property tests were also prepared and tested. The glow discharge spectrometer [24] was used for the chemical property tests, and the hydraulic universal testing machine was used for the mechanical property tests.

The present study was focused on the effects of corrosion on the chemical and mechanical properties for three different grades of structural steels. Three dry or water-immersed conditions were considered: air, freshwater immersion, and seawater immersion. The mixture of dry and water-immersed conditions as in case of water ballast tanks of ships was not considered. Three temperature conditions were considered: room temperature (18^{o}C) and two cold conditions with a temperature of 0^{o}C and -10^{o}C. Any artificial acceleration of the corrosion was not attempted, but rather the corrosion was naturally progressed during a period of 12 months. The chemical and mechanical properties of test specimens were measured before and after the corrosion testing. Based on the test results, the characteristics of the corrosion progression rate were studied and reported in a separate paper [25].

2. Test Specimens

2.1 Types of Specimens

Two groups of test specimens were prepared, i.e., one for mechanical properties and the other for chemical properties.

For measuring the mechanical properties, the corrosion test specimens were fabricated in exactly the same shape as for tensile coupon test specimens as shown in Figure 1, where the geometric specifications of the American Society for Testing and Materials (ASTM) E8 was applied [26], with a gauge length of 60 mm, and thickness 6 mm. The mechanical properties of the test specimens were measured through the tensile coupon tests before and after the corrosion testing. On the other hand, square shaped specimens with a size of 20 mm × 20 mm × 6 mm were prepared for measuring the chemical properties.

Three types of structural steels were used in the corrosion testing, namely mild steel (grade A), AH32 steel, and DH32 steel. A total of eighteen test specimens for each steel grade were prepared for observing the effects of corrosion at different temperature and environmental conditions.

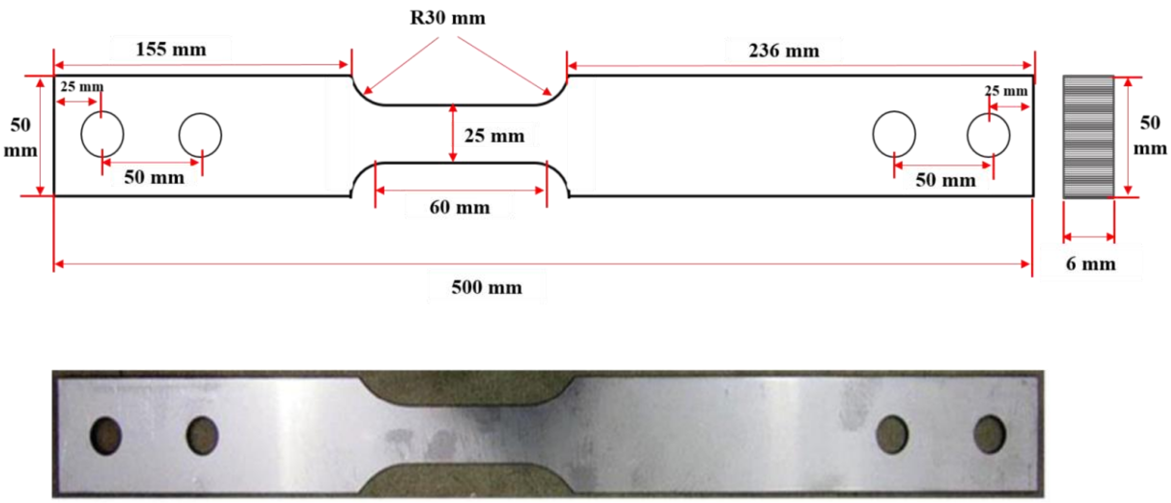


Figure 1. Geometric details of the test specimens.

Table 1. Chemical composition of structural steels before corrosion obtained using the GDS method.

Element	Composition of specimen before corrosion (%)		
	Mild steel (Grade A)	AH32 steel	DH32 steel
C	0.22399	0.17497	0.19032
Mn	0.63994	0.97997	1.467
P	0.03099	0.03199	0.031
S	0.02797	0.02600	0.02602
Si	0.30098	0.27000	0.37603
Cu	0.30997	0.320	0.313
Ni	0.35992	0.35201	0.35796
Cr	0.18900	0.202	0.20499
Mo	0.05189	0.05588	0.0651
Al	0.01700	0.015	0.016

2.2 Chemical Properties of Intact Specimens

The chemical composition of steel is a fundamental factor which determines the mechanical properties of material. Due to this fundamental role, strict controls on the composition of steel is being applied during its production in European countries according to applicable European standards [27]. The chemical properties of intact specimens obtained using the GDS (glow discharge spectrometer) method [24] before starting corrosion testing at room temperature (18^{o}C) are indicated in Table 1.

2.3 Mechanical Properties of Intact Specimens

Quasi-static tensile coupon tests with a speed of 0.05 mm/s or a strain rate of 0.001/s were conducted to obtain the mechanical properties of intact specimens, i.e., before starting corrosion tests. A universal test machine with loading capacity of 1,000 kN, shown in Figure 2, at the International Centre for Advanced Safety Studies / Korea Ship and Offshore Research Institute (www.icass.center) in South Korea was used.

The test results associated to mechanical properties are presented in Table 2. It was observed that DH32 steel has the highest elastic modulus (233.4 GPa), followed by AH32 steel (209.6 GPa) and mild steel (198.6 GPa). The yield strength, ultimate tensile strength and fracture strength of the three grades of steels followed the similar trend as the elastic modulus that is the highest for DH32 steel followed by AH32 steel and mild steel.

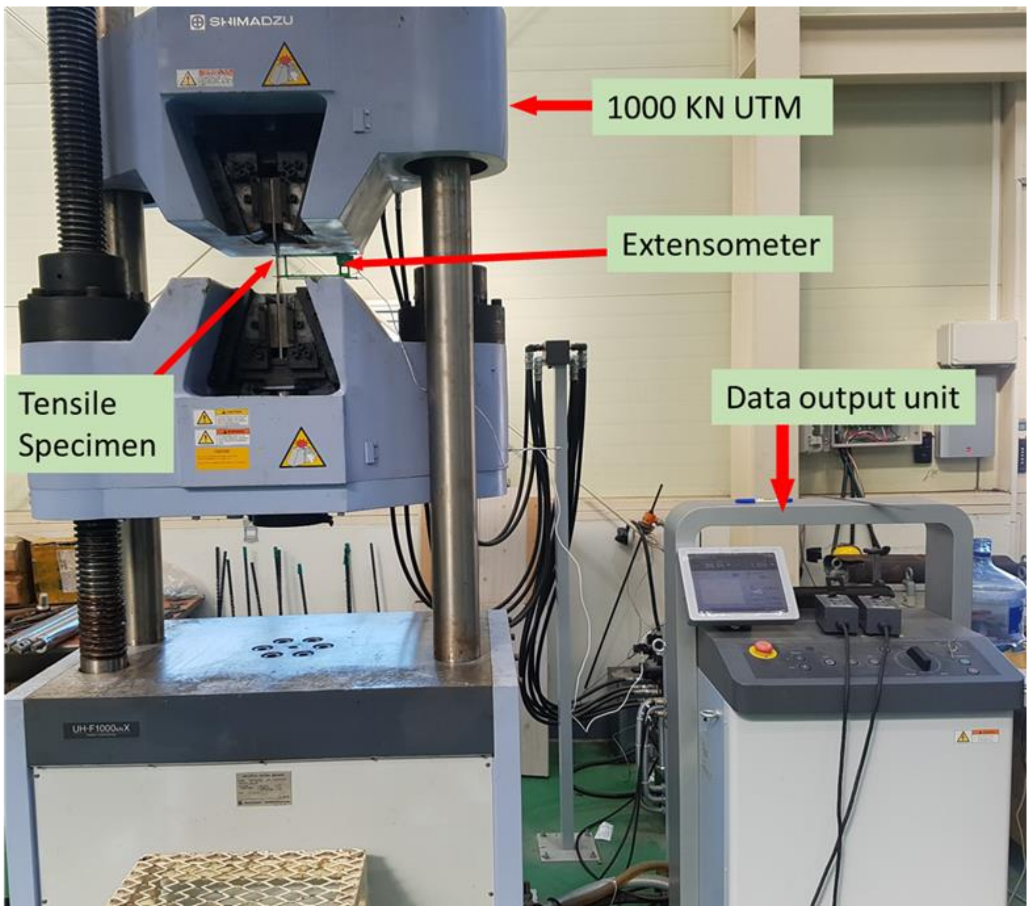


Figure 2. Test set-up for tensile coupon tests using the universal test machine with a loading capacity of 1,000 kN.

Table 2. Mechanical properties of mild and high strength steels before corrosion

Steel grade	E (GPa)	σ_Y (MPa)	σ_T (MPa)	σ_f (MPa)	ε_Y (%)	ε_T (%)	ε_f (%)
Mild grade A	198.6	331.3	485.4	378.4	2.2	19.2	37.8
AH32	209.6	360.5	555.0	416.7	1.4	16.3	32.3
DH32	233.4	364.7	540.7	419.5	1.4	16.5	34.9

Note [5]: E is the elastic modulus, σ_Y is the yield strength, σ_T is the ultimate tensile strength, σ_f is the fracture strength which is the strength at failure strain, i.e., where the tensile coupon test specimen is separated into two pieces, ε_Y is the yield strain which is the strain at the yield point, ε_T is the ultimate tensile strain which is the strain at the ultimate tensile strength, and ε_f is the fracture strain which is the elongation where the test specimen is separated into two pieces.

3. Methods for Corrosion Tests

Naturally-progressed corrosion was allowed to develop in different dry or water-immersed conditions by keeping the tensile specimens in fully submerged or in open air at different temperatures. Two specimens from each steel grade were immersed in three dry or water-immersed conditions, namely air (dry), freshwater immersion and seawater immersion.

3.1 Dry and Water-immersed Condition Control

The specimens were kept fully submerged in 3000 ml seawater or freshwater to maintain water-immersed condition and in the air to achieve dry condition, respectively. The sea and freshwater in the test trays were regularly renewed at an interval of week for maintaining pH and providing sufficient oxidation to the specimens like in real fields of operation. The seawater was collected from the seashore at Haeundae area in Busan, South Korea. The tab water was used for the freshwater immersion tests. The salinity of sea and freshwater was measured using a salinity meter. It was found that the average value of salinity was 2.5% for seawater and 1.6% for freshwater, respectively. The presence of average dissolved oxygen was measured as 9 mg/l and 10.8 mg/l using DO metre for seawater and freshwater respectively.

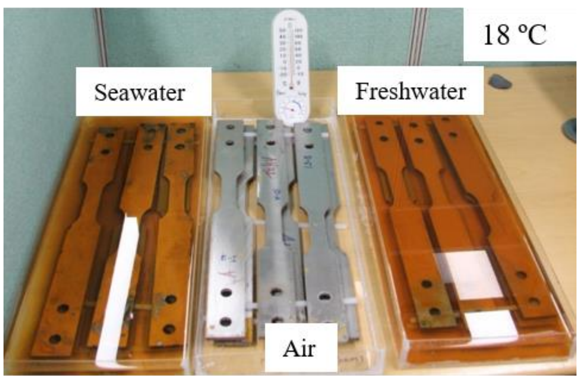
3.2 Temperature Control

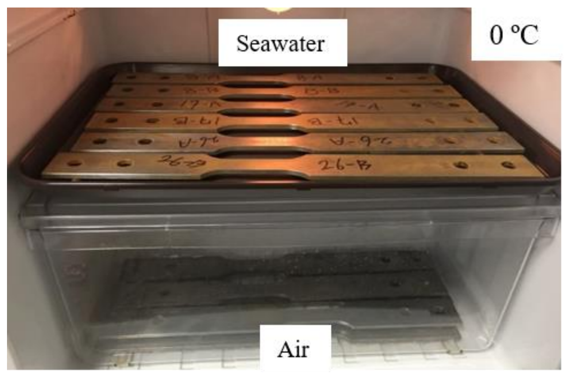
Three different temperature conditions were considered: 18^{o}C, 0^{o}C and -10^{o}C. The temperatures 0^{o}C and -10^{o}C represent structural steels subjected to corrosion in cold environmental conditions, while 18^{o}C temperature represents the corrosion at normal room temperature for direct comparison of the test results. The temperature conditions for 0^{o}C and -10^{o}C were maintained inside refrigerators. A total of six specimens for each steel grade were tested for three different temperature conditions as shown in Figure 3.

3.3 Method for Measuring the Corrosion Wear with Time

The test specimens were carefully cleaned up with the help of sandpaper and weighed initially before they were kept fully submerged in seawater or freshwater at three different temperatures. Corrosion was allowed in each of the environmental conditions under control in the laboratory. At an interval of 4 weeks, the corrosion rust on the surface of each specimen was cleaned up with the help of fine and medium sandpapers and rinsed by distilled water. While removing rust from the surface of specimens, all the precautions were taken, and cleaning was performed by hand to avoid any loss of mass due to excessive abrasion of the material surface. The mass of cleaned specimen was then measured precisely by using a weighing machine with 1-gram precision.

The measured mass loss of specimen was converted to an equivalent loss of thickness, assuming that the corrosion occurred uniformly over the surface of specimen. To obtain more accurate data of mass loss at every month interval, the average mass of two specimens was calculated. The average mass loss of test specimens or equivalent loss of thickness has been reported in a separate paper [25]. The typical images of the specimen kept fully immersed in seawater, freshwater and air conditions with three different temperatures are presented in Figure 3.

(a) 

(b) 

(c) 

Figure 3. Test specimens kept in dry or water-immersed condition in seawater, freshwater and air at (a) 18^{o}C, (b) 0^{o}C and (c) -10^{o}C.

4. Test Results on the Chemical Properties of Corroded Specimens

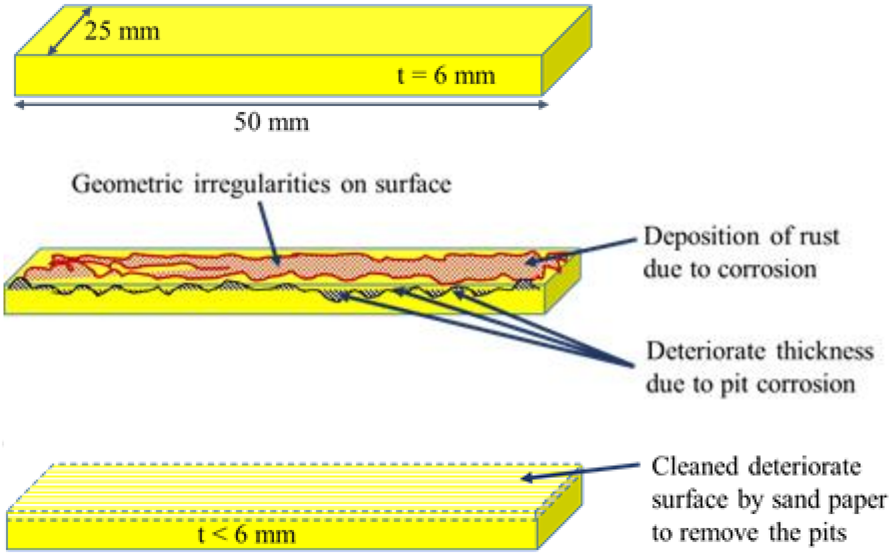
The chemical composition of mild steel (with grade A), AH32 steel, and DH32 steel were measured after the progression of corrosion in seawater submerged condition at a temperature of 18^{o}C, 0^{o}C and -10^{o}C. The motivation of the present paper was initiated to acquire the test database on the corrosion of ship structural steel exposed to the corrosive marine environment which may affect the chemical composition of steel. Maximum corrosion was expected to be observed in seawater submerged condition, and thus only the effect of seawater submergence on chemical composition of three different steel grades was analyzed (for the reasons of cost, etc.).

As would be expected, the measured results of chemical properties for corroded structural steels under seawater immersion condition with different temperatures for a period of 12 months were exactly the same as intact specimens, as indicated in Table 1. It is obvious that corrosion does not change the chemical properties of steel.

5. Test Results on the Mechanical Properties of Corroded Specimens

As reported in [25], maximum corrosion wastage was observed in all the three types of specimens at 18^{o}C (warmest) under seawater submerged condition. AH32 and DH32 steel experienced faster corrosion progress rate than mild steel.

The mechanical properties of corroded steels were identified through quasi-static tensile testing. It should be noted that due to corrosion the surface of specimens become uneven because of the formation of micro-pits on the surface, as illustrated in Figure 4. Therefore, identifying the real cause of change in the mechanical properties of material is challenging in association with irregular surface geometry due to corrosion.



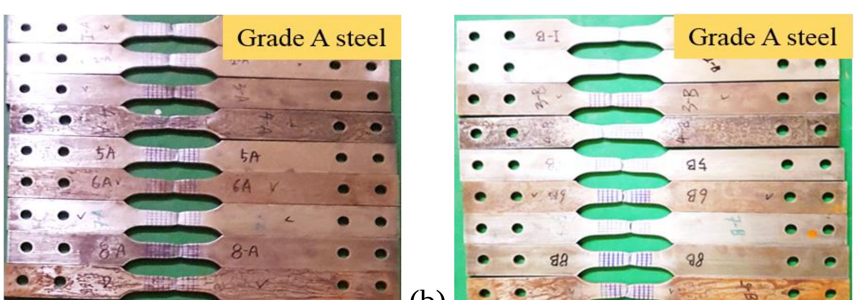
(a) (b) (c)

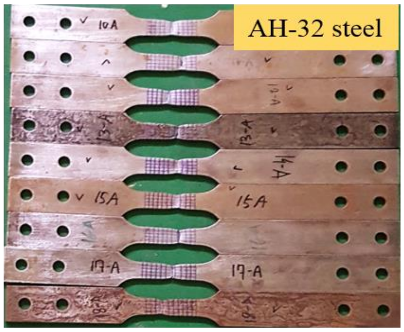
Figure 4. Schematic of tensile coupon test specimen in the gauge length zone before and after corrosion, (a) intact (uncorroded) specimen without corrosion, (b) corroded specimen, (c) cleaned specimen.

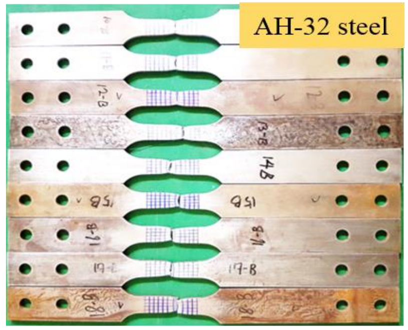
In this regard, two specimens have been tested under the same corrosive environment. One of them was used to measure the mechanical properties by removing the surface rust only in the gauge length zone, and the other was significantly cleaned up to achieve flat surface by removing uneven surface of micro-pits with the help of sandpaper. The first specimen was called “corroded specimen” and the second was called “cleaned specimen”.

Figure 5 shows the specimens after tensile coupon testing. It was observed that mild steel (grade A) was relatively more ductile than AH32 and DH32 steels, where the failure surface of specimens showed an arched shape, ensuring the mode of ductile failure. The maximum time to reach breaking point (failure) was about 10 min. for mild steel, 7 min. for AH32 steel, and 8 min. for DH32 steel, respectively.

The test results of the mechanical properties such as Young’s modulus, yield strength, ultimate tensile strength, failure strength, yield strain, ultimate strain and failure strain for grades A, AH32 and DH32 are documented in Tables 3 to 5. Figures 6 to 8 present the engineering stress-engineering strain curves of corroded steels in association with “corroded specimen” and “cleaned specimen”, as illustrated in Figure 3. Figures 13 to 18 focus on the yield strength and ultimate tensile strength characteristics of corroded steels.

(a)  (b)

(c) 

(d) 

(e) 

(f) 

Figure 5. Specimens after tensile coupon testing: (a), (c) and (e) for "corroded specimen" and (b), (d) and (f) for "cleaned specimen".

Table 3. Mechanical properties of mild steel (grade A)

Submerged condition	Temp (°C)	ID	Surface condition	E (GPa)	σ_Y (MPa)	σ_T (MPa)	σ_f (MPa)	ε_Y (%)	ε_T (%)	ε_f (%)
-	18	A	Uncorroded	198.6	331.3	485.4	378.4	0.022	0.192	0.378
Air	18	1-A	Corroded	221.1	315.2	468.6	360.1	0.020	0.195	0.379
	18	1-B	Cleaned	199.6	329.7	483.0	376.5	0.022	0.19	0.375
	0	2-A	Corroded	197.3	315.6	472.0	363.6	0.021	0.194	0.385
	0	2-B	Cleaned	201.9	320.0	478.6	368.7	0.021	0.193	0.384
	-10	3-A	Corroded	217.4	322.7	475.8	367.3	0.020	0.196	0.376
	-10	3-B	Cleaned	212.7	323.5	474.6	367.4	0.022	0.195	0.384
Freshwater	18	4-A	Corroded	220.8	313.4	467.9	361.5	0.018	0.198	0.382
	18	4-B	Cleaned	204.2	324.9	472.4	365.8	0.009	0.191	0.353
	0	5-A	Corroded	215.9	327.3	472.3	364.5	0.007	0.194	0.382
	0	5-B	Cleaned	203.7	327.1	476.6	368.1	0.021	0.198	0.384
	-10	6-A	Corroded	208.2	321.3	472.2	362.8	0.008	0.197	0.383
	-10	6-B	Cleaned	199.4	324.1	477.2	369.2	0.020	0.196	0.377

Seawater	18	7-A	Corroded	219.5	326.1	472.5	364.2	0.013	0.196	0.373
	18	7-B	Cleaned	199.7	326.3	475.5	370.4	0.021	0.199	0.370
	0	8-A	Corroded	222.6	322.2	471.1	363.6	0.017	0.195	0.380
	0	8-B	Cleaned	213.4	318.8	472.3	364.3	0.021	0.201	0.383
	-10	9-A	Corroded	215.5	323.9	470.7	363.0	0.019	0.194	0.381
	-10	9-B	Cleaned	218.3	328.8	477.8	368.4	0.019	0.194	0.382

Table 4. Mechanical properties of AH32 steel

Submerged condition	Temp (°C)	ID	Surface condition	E (GPa)	σ_Y (MPa)	σ_T (MPa)	σ_f (MPa)	ε_Y (%)	ε_T (%)	ε_f (%)
-	18	AH32	Uncorroded	209.6	360.5	555.0	416.7	0.014	0.163	0.323
Air	18	10-A	Corroded	210.9	358.4	551.7	414.2	0.014	0.161	0.320
	18	10-B	Cleaned	210.6	359.9	551.5	410.4	0.014	0.162	0.323
	0	11-A	Corroded	209.7	359.1	551.3	420.4	0.014	0.155	0.303
	0	11-B	Cleaned	214.0	358.1	549.9	420.5	0.003	0.163	0.328
	-10	12-A	Corroded	205.9	358.7	548.7	419.3	0.015	0.168	0.327
	-10	12-B	Cleaned	205.5	359.2	547.5	418.9	0.005	0.157	0.328
Freshwater	18	13-A	Corroded	209.9	352.5	539.6	419.6	0.015	0.163	0.317
	18	13-B	Cleaned	200.4	359.3	546.7	416.7	0.011	0.165	0.328
	0	14-A	Corroded	210.8	355.9	549.8	421.3	0.014	0.161	0.331
	0	14-B	Cleaned	216.2	359.7	552.9	417.0	0.002	0.161	0.337
	-10	15-A	Corroded	217.4	355.1	551.7	421.9	0.002	0.161	0.314
	-10	15-B	Cleaned	206.8	358.2	549.5	419.6	0.013	0.158	0.324
Seawater	18	16-A	Corroded	224.6	353.4	534.2	419.0	0.015	0.165	0.31
	18	16-B	Cleaned	217.5	359.6	543.5	410.5	0.014	0.162	0.319
	0	17-A	Corroded	209.7	353.9	546.5	419.8	0.013	0.168	0.325
	0	17-B	Cleaned	194.4	358.5	553.6	425.6	0.014	0.168	0.337
	-10	18-A	Corroded	219.6	355.2	550.3	415.5	0.012	0.162	0.313
	-10	18-B	Cleaned	215.5	357.4	550.8	410.5	0.014	0.161	0.321

Table 5. Mechanical properties of DH32 steel

Submerged Condition	Temp (°C)	ID	Surface condition	E (GPa)	σ_Y (MPa)	σ_T (MPa)	σ_f (MPa)	ε_Y (%)	ε_T (%)	ε_f (%)
-	18	DH32	Uncorroded	233.4	364.7	540.7	419.5	0.014	0.165	0.349
Air	18	19-A	Corroded	233.0	353.9	538.0	417.4	0.013	0.164	0.348
	18	19-B	Cleaned	199.3	351.2	537.4	409.9	0.016	0.164	0.325
	0	20-A	Corroded	207.6	352.5	534.7	420.7	0.014	0.170	0.308
	0	20-B	Cleaned	198.8	352.0	536.5	418.8	0.016	0.172	0.352
	-10	21-A	Corroded	208.7	360.9	537.2	431.1	0.014	0.169	0.308
	-10	21-B	Cleaned	198.4	352.4	535.1	412.3	0.016	0.167	0.351
Freshwater	18	22-A	Corroded	225.8	347.3	529.7	399.1	0.015	0.167	0.337
	18	22-B	Cleaned	189.9	353.1	537.3	439.1	0.009	0.167	0.314
	0	23-A	Corroded	220.5	360.3	535.1	407.8	0.005	0.164	0.313
	0	23-B	Cleaned	193.7	360.8	537.9	416.2	0.017	0.17	0.343
	-10	24-A	Corroded	220.6	359.0	535.7	408.2	0.005	0.164	0.312
	-10	24-B	Cleaned	193.0	362.3	540.1	416.6	0.016	0.169	0.342
Seawater	18	25-A	Corroded	229.6	359.47	538.7	402.7	0.013	0.166	0.341
	18	25-B	Cleaned	212.2	361.2	539.2	412.4	0.004	0.158	0.323
	0	26-A	Corroded	225.4	356.6	534.6	399.3	0.012	0.165	0.335
	0	26-B	Cleaned	212.3	354.0	534.0	421.1	0.016	0.163	0.321
	-10	27-A	Corroded	214.1	358.3	534.2	410.8	0.003	0.166	0.320
	-10	27-B	Cleaned	213.4	362.8	539.8	411.9	0.003	0.167	0.326

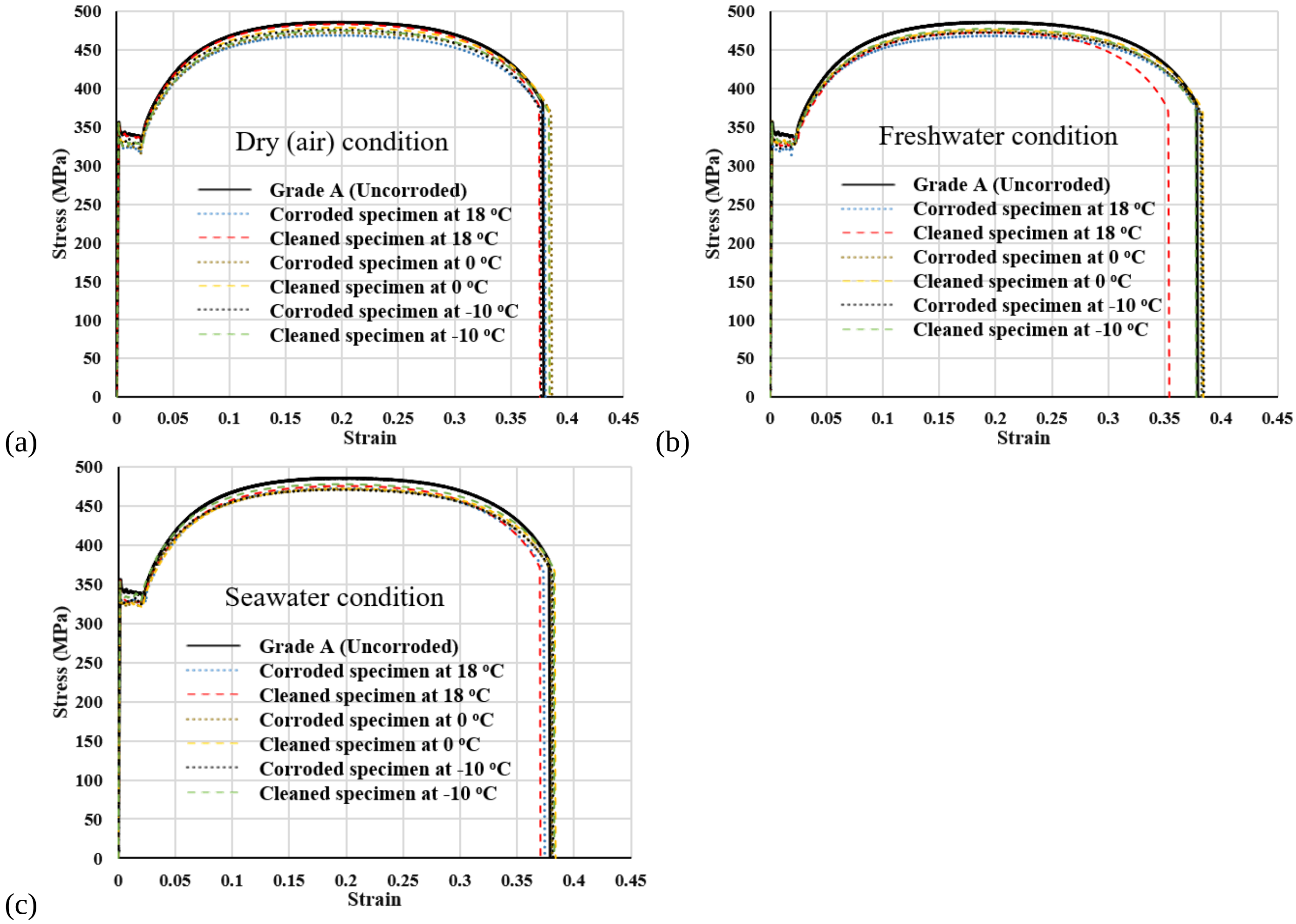
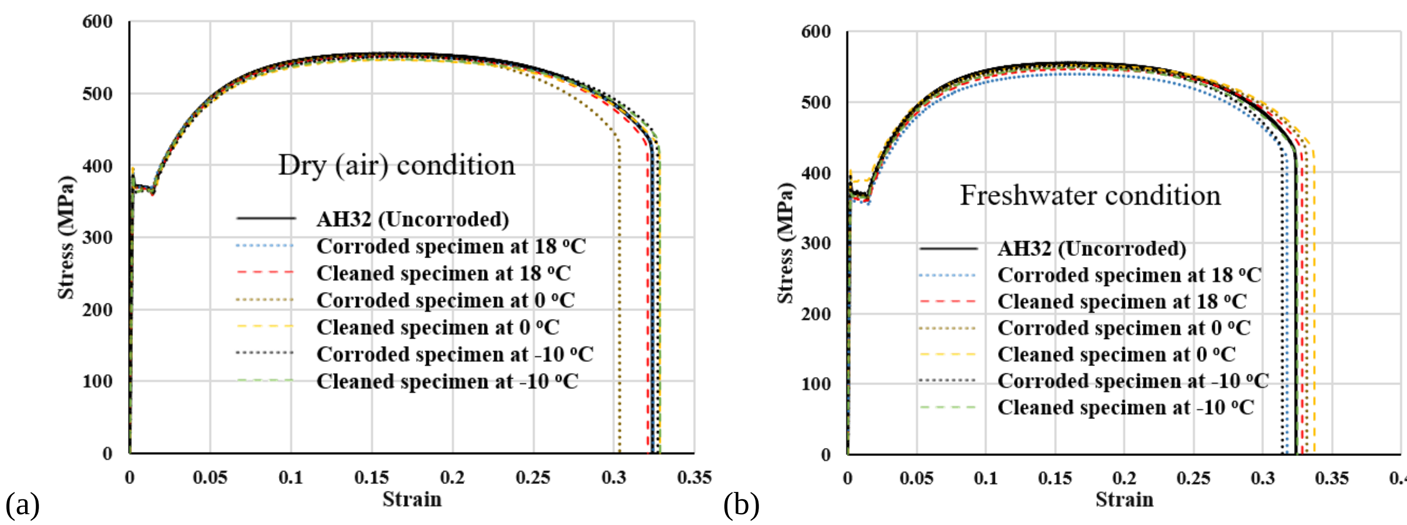


Figure 6. Engineering stress-engineering strain curves of mild steel (grade A) in (a) dry (air) condition, (b) freshwater condition, and (c) seawater condition.



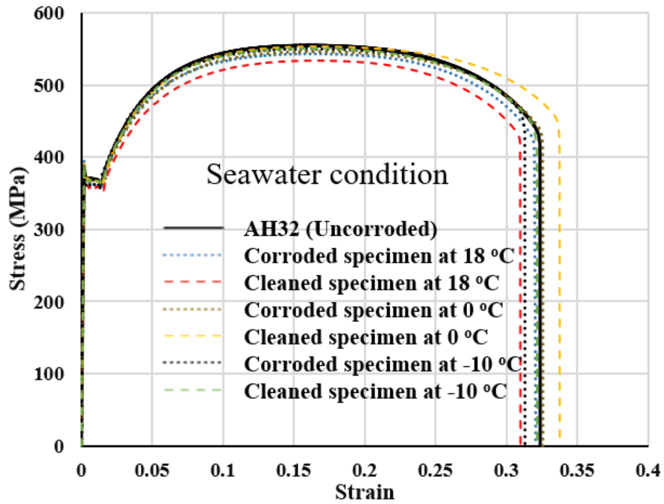


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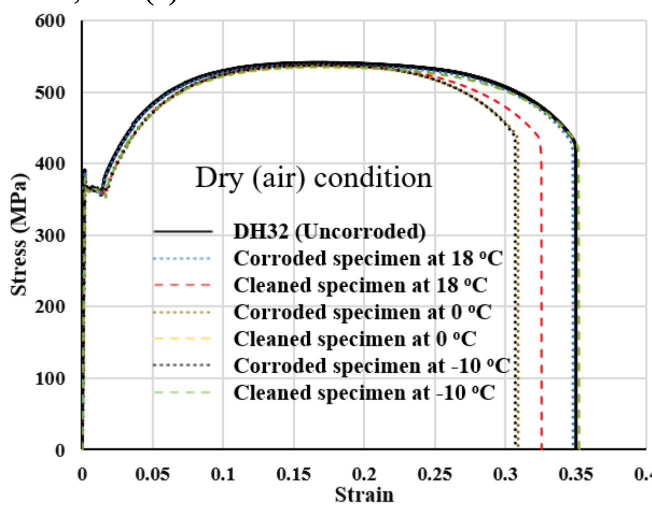
Figure 7. Engineering stress-engineering strain curves of AH32 steel in (a) dry (air) condition, (b) freshwater condition, and (c) seawater condition.



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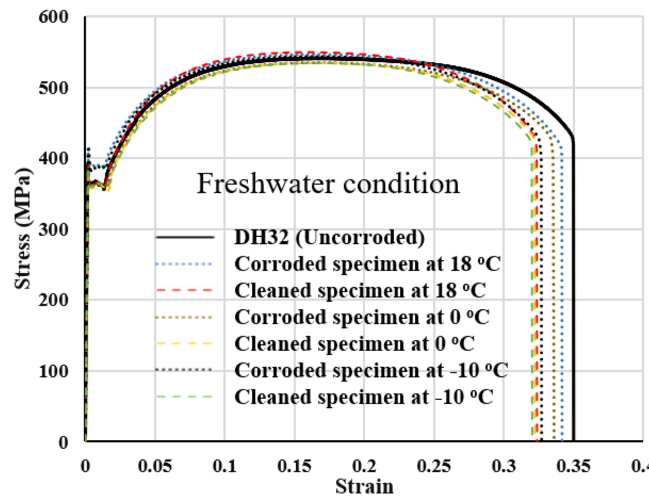

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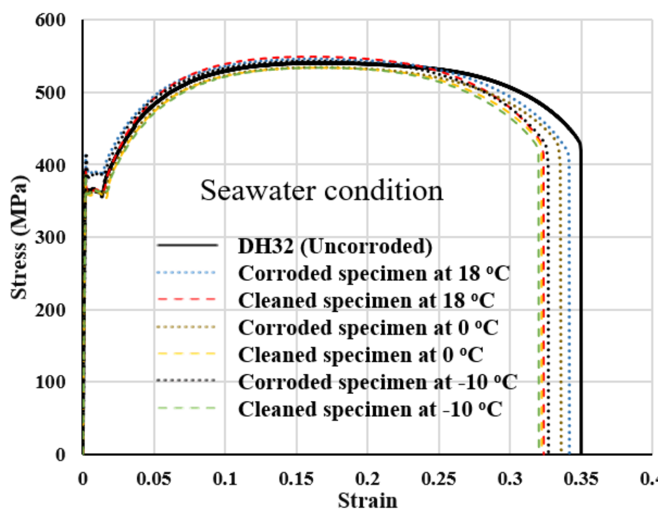

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Figure 8. Engineering stress-engineering strain curves of DH32 steel in (a) dry (air) condition, (b) freshwater condition, and (c) seawater condition.

5.1 Effects of Dry or Water-Immersed Conditions at Different Temperatures

5.1(a) Room Temperature (18^{o}C)

Tensile coupons of mild steel (grade A) exposed in dry (air) condition at 18^{o}C showed that the yield strength and ultimate tensile strength of corroded specimen was reduced by 4.86% and 3.5% in comparison to intact tensile specimen, respectively. However, cleaned surface specimen (with removal of deteriorated surface at gauge area) kept in water-immersed (freshwater) condition showed 4.6% and 0.96% increase in the yield and ultimate tensile strength respectively in comparison to corroded specimen values. The specimen kept in water-immersed (seawater) condition revealed that the yield strength of corroded and cleaned specimen remained almost unchanged, and the ultimate tensile strength of cleaned specimen was found to increase by 0.64% which is still negligible. The fracture strains for both specimens were almost unchanged equal to the original uncorroded specimen in air, freshwater, and seawater submerged conditions.

AH32 steel specimen kept in dry (air) condition at 18^{o}C indicated 2.5% increase in the yield strength for cleaned specimen in comparison to corroded specimen. Moreover, in freshwater submerged condition, the cleaned specimen showed 2% and 1.2% increase in the yield and ultimate tensile strength, respectively, see Table 3. In seawater immersion condition, the yield strength and ultimate tensile strength of cleaned specimen was increased by 1.6% and 2%, respectively as compared to corroded specimen values.

It was noted that the corroded and cleaned specimen of DH32 steel kept in dry condition did not show any significant variation in the yield and ultimate tensile strength, which may arise from insignificant progress of corrosion. However, the fracture strain was reduced slightly in case of cleaned specimen. Further, in freshwater immersion condition, the cleaned specimen of DH32 steel indicated 2.8% and 1.5% increase in the yield and ultimate tensile strength, respectively in comparison to corroded specimen, see Table 4. The cleaned specimen in seawater condition showed similar ultimate tensile strength as that of corroded specimen but with an increased fracture strength by 2.5% which was close to the original value of uncorroded specimen.

5.1(b) Cold Temperature (0 ^{o}C)

Mild steel (grade A) specimen kept in dry (air) condition at 0^{o}C revealed that the yield strength, ultimate tensile strength and fracture strength of corroded specimen were reduced by 4.8%, 3.5% and 4.8%, respectively in comparison to the intact specimen. However, in case of cleaned specimen, almost similar values of the yield strength and fracture strength were observed to the intact specimen, see Table 2. The fracture strain remained almost unchanged for each specimen. In freshwater immersion condition, the ultimate tensile strength and fracture strength of cleaned specimen increased by 0.8% and 1%, respectively, while no change was found in the yield strength. The cleaned and corroded specimen in seawater immersion condition showed very slight increase in ultimate tensile and fracture strength of cleaned specimen. The fracture strain remained almost unchanged for each specimen.

Cleaned specimens of AH32 steel kept in dry (air) condition at 0^{o}C indicated an increase of 1.1% and 8% in the yield strength and fracture strain in comparison to corroded specimens. Further, in case of freshwater immersion condition, the cleaned specimen showed 5.5% and 0.5% increase, respectively in the yield and ultimate tensile strength, see Table 3. In seawater immersion condition, the ultimate tensile strength, fracture strength and fracture strain of cleaned specimen were found to increase by 1.2%, 1.4% and 3.7%, respectively.

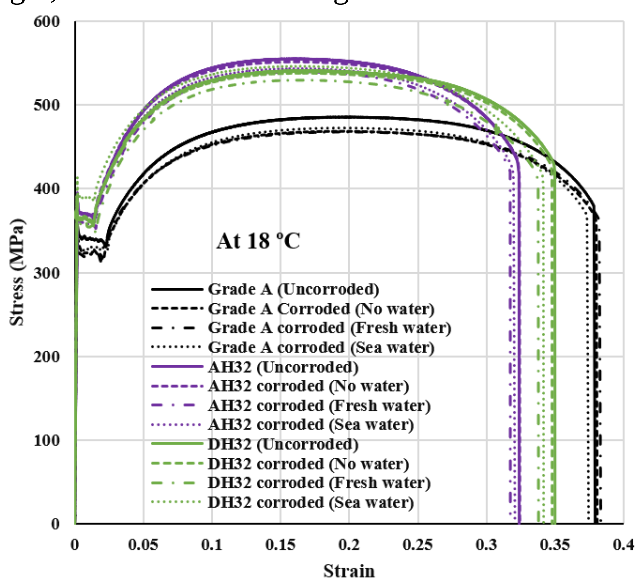
Corroded and cleaned specimen of DH32 steel kept in dry (air) condition did not indicate any significant variation in the yield or ultimate tensile strength. The fracture strain increased by 16% in case of cleaned specimen, but this may be due to the effect of geometric wear (due to unsuccessful micro-pit cleaning) rather than a material property perspective. In freshwater immersion condition, the cleaned DH32 specimen showed 2.1%, 2.6% and 2.2% increase, respectively in the yield strength, ultimate tensile and fracture strength in comparison to corroded specimen, see Table 4. Cleaned specimen in seawater immersion condition showed 5.5% increase in the fracture strength than that of corroded specimen. No significant variation was found in the yield and ultimate tensile strength.

5.1(c) Very Cold Temperature (-10^{o}C)

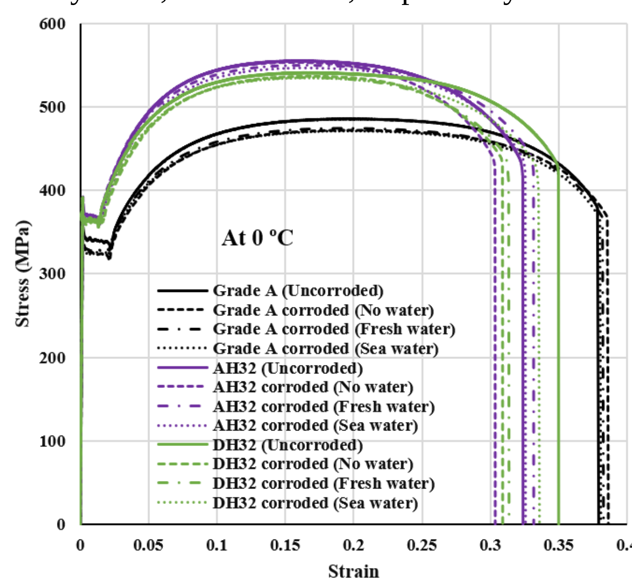
Corroded and cleaned specimens of mild steel (grade A) kept in dry (air) condition at -10^{o}C indicated an insignificant variation in the mechanical properties. Moreover, the yield and ultimate tensile strength of corroded and cleaned specimen slightly decreased in comparison to the original uncorroded specimen. In freshwater immersion condition, the yield, ultimate tensile, and fracture strength of cleaned specimen was found to increase by 0.9%, 1% and 2%, respectively as compared to corroded specimen. In seawater immersion condition, the yield, ultimate tensile and fracture strength were increased by 1.5%, 1.4% and 1.3%, respectively in comparison to corroded specimen.

AH32 steel specimen in dry (air) condition at -10^{o}C showed 1.1% increase in the yield strength of cleaned specimen compared to corroded specimen. Moreover, in freshwater immersion condition, there was insignificant variation in the yield, ultimate tensile and fracture strength, but the fracture strain of cleaned specimen was increased by 3.1%, see Table 3. In seawater immersion condition, the yield strength and fracture strain of cleaned specimen was increased by 2.2% and 2.5%, respectively compared to corroded specimen.

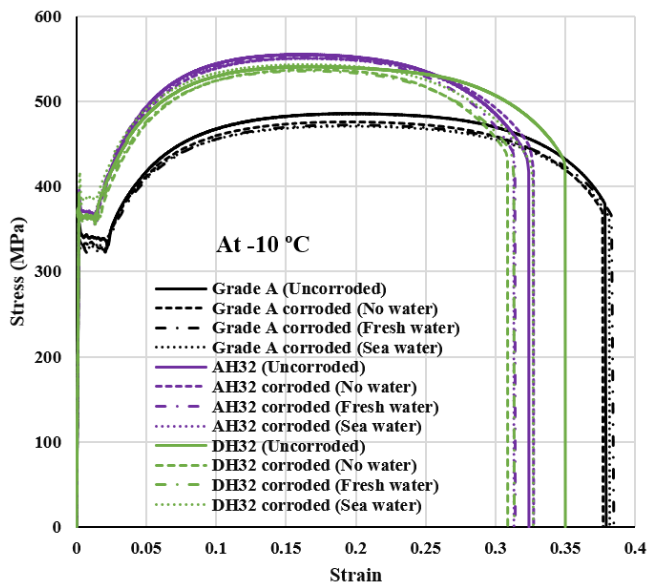
Corroded and cleaned specimens of DH32 steel exposed in dry (air) condition did not show any significant variation in the yield, ultimate tensile and fracture strength, but the fracture strain of cleaned specimen significantly increased by 14% in comparison to corroded specimen. This may again be due to the effect of geometric wear rather than a material property perspective. In freshwater immersion condition at -10^{o}C, the yield, ultimate tensile, fracture strength, and fracture strain of cleaned specimen were increased by 1.9%, 2.8%, 2% and 9.6%, respectively in comparison to corroded specimen. In seawater immersion condition, the yield strength, ultimate tensile strength and fracture strain increased by 5.2%, 1.6% and 2%, respectively.



(a)



(b)



(c)

Figure 9. Comparison of engineering stress-engineering strain curves of steels at (a) 18 ^{o}C, (b) 0 ^{o}C and (c) -10 ^{o}C.

5.2 Effects of Temperature in Dry or Water-Immersed Conditions

5.2(a) Dry (Air) Condition

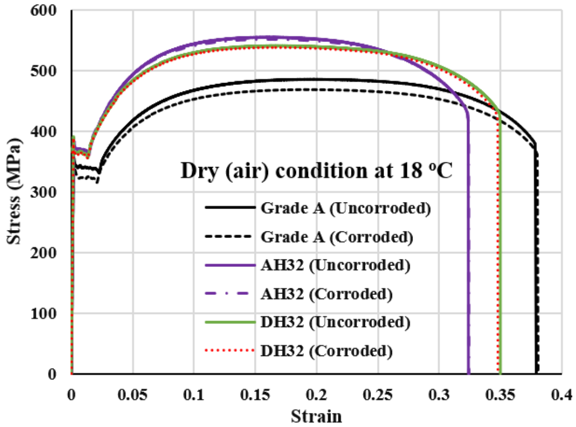
Corroded specimens of mild steel (grade A) indicated 3.5%, 2.7% and 2% reduction in the ultimate tensile strength at 18^{o}C, 0^{o}C, -10^{o}C, respectively. No significant change was noticed in the ultimate tensile strength for AH32 and DH32 steel, see Figure 10 together with Figures 13 to 18.

5.2(b) Freshwater Condition

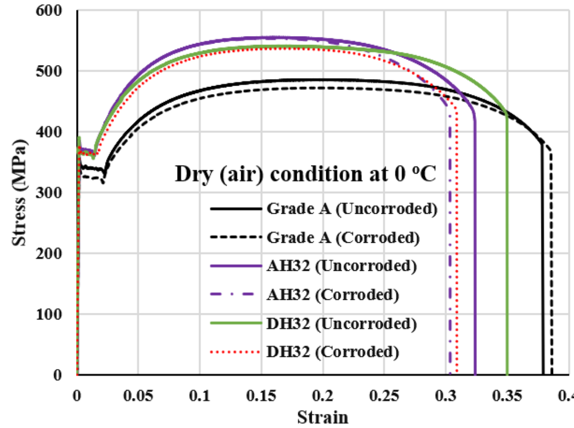
Mild steel specimens experienced the maximum reduction in the ultimate tensile strength among all three materials at room temperature, see Figure 11. Corroded specimens of mild steel showed 3.7%, 2.7% and 2.7% decrease in comparison to the ultimate tensile strength of intact specimen at 18^{o}C, 0^{o}C, -10^{o}C, respectively. The ultimate tensile strength of AH32 and DH32 steel was decreased by 2.8% and 1.2% at 18^{o}C, 0.6% and 2% at 0^{o}C, and 0.9% and 0.8% at -10^{o}C, respectively.

5.2(c) Seawater Condition

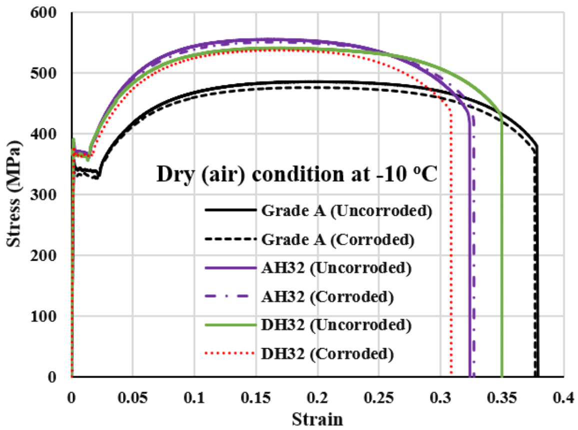
Mild steel specimen at 18^{o}C, 0^{o}C, -10^{o}C showed a decrease in the ultimate tensile strength by 2.7%, 2.8% and 2.9% in comparison to the original specimen, respectively. However, the ultimate tensile strength of AH32 steel was decreased by 3.7%, 1.6% and 0.8% at 18^{o}C, 0^{o}C, -10^{o}C, respectively. The ultimate tensile strength of DH32 steel was increased by 1% compared to the intact specimen at 18 ^{o}C and decreased by 1.1% at both 0^{o}C and -10^{o}C temperature, see Figure 12. Similar to mild steel and AH32 steel, it was again observed that the mechanical properties of steels were not affected by corrosion, as shown in Figures 13 to 18. It was considered that slight differences in mechanical properties were due to potential errors of tensile coupon testing together with the effects of geometric corrosion wear rather than material properties themselves.



(a)

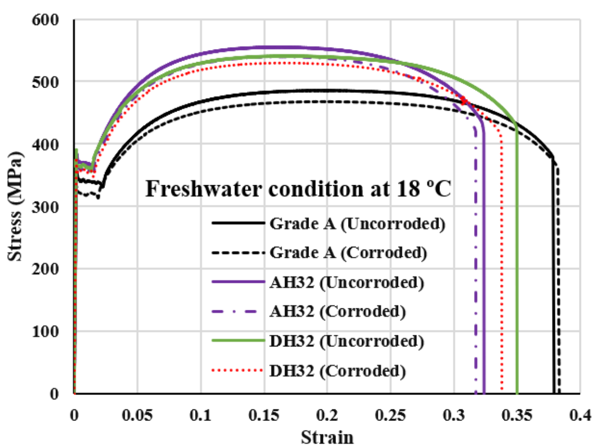


(b)

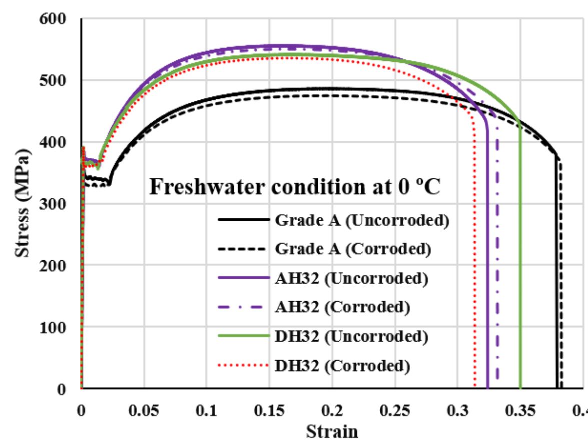


(c)

Figure 10. Comparison of engineering stress-engineering strain curves of steels in air condition at (a) room temperature (18^{o}C), (b) 0^{o}C and (c) -10^{o}C.



(a)



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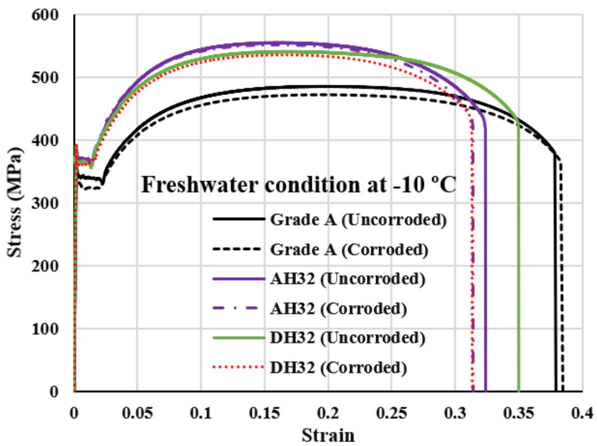
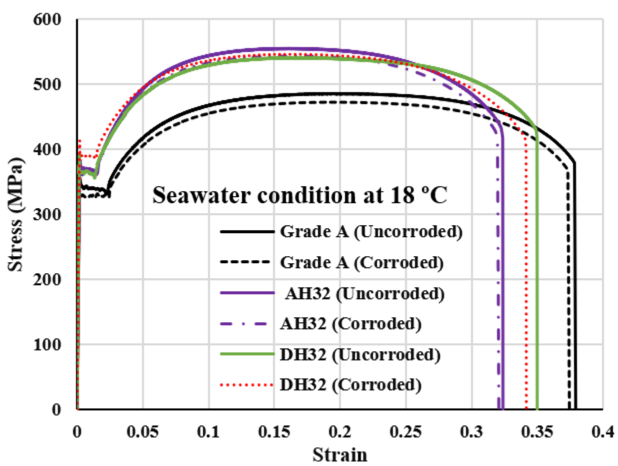
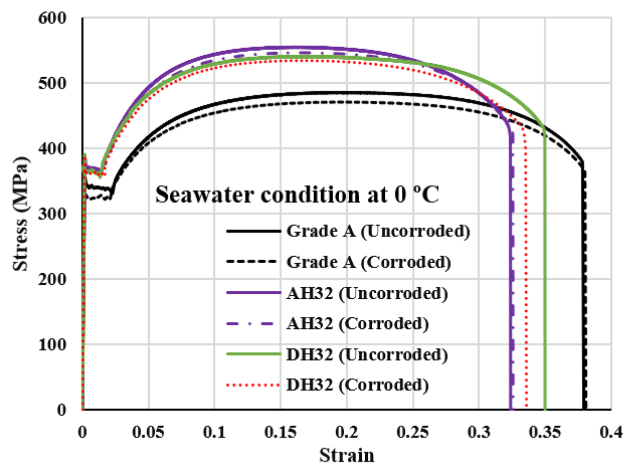


(c)

Figure 11. Comparison of engineering stress-engineering strain curves of steels in freshwater condition at (a) room temperature (18^{o}C), (b) 0^{o}C and (c) -10^{o}C.



(a)



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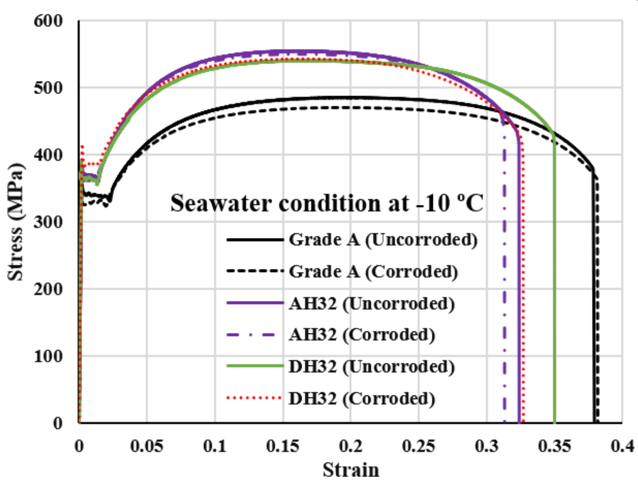


(c)

Figure 12. Comparison of engineering stress-engineering strain curves of steels in seawater condition at (a) room temperature (18^{o}C), (b) 0^{o}C and (c) -10^{o}C.

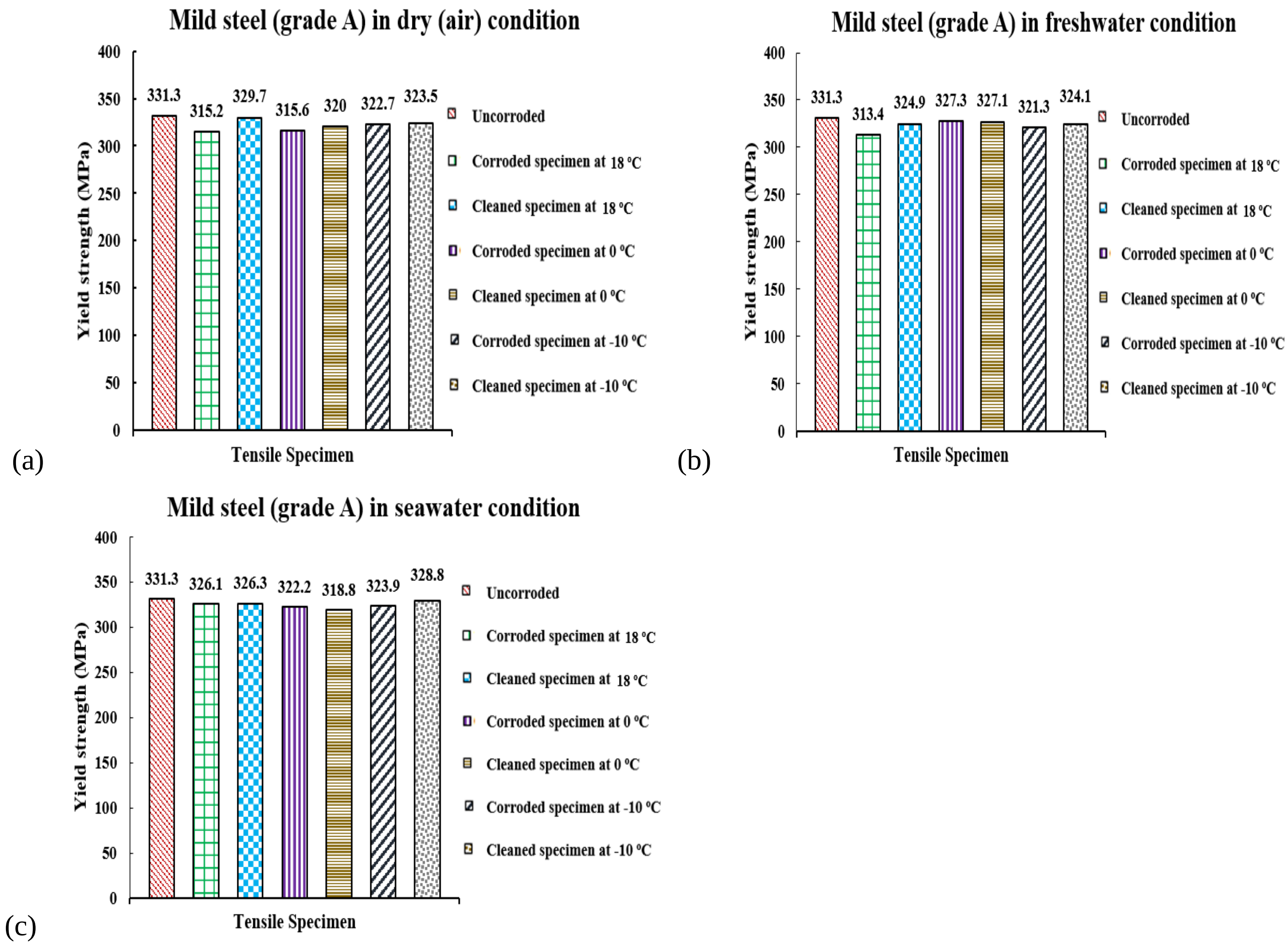
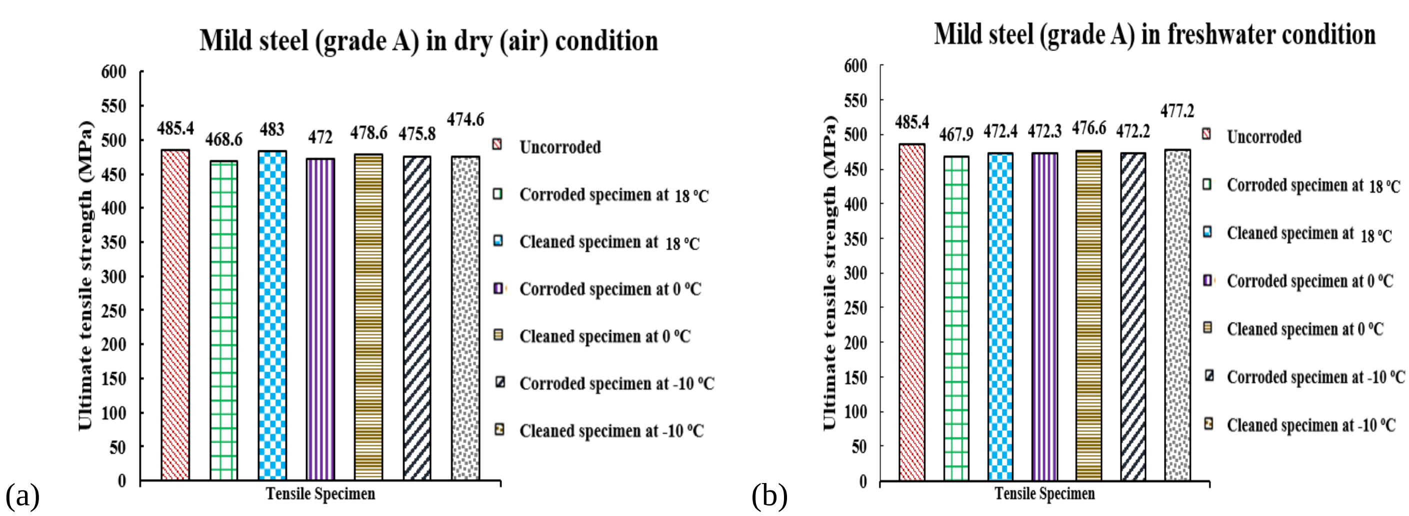
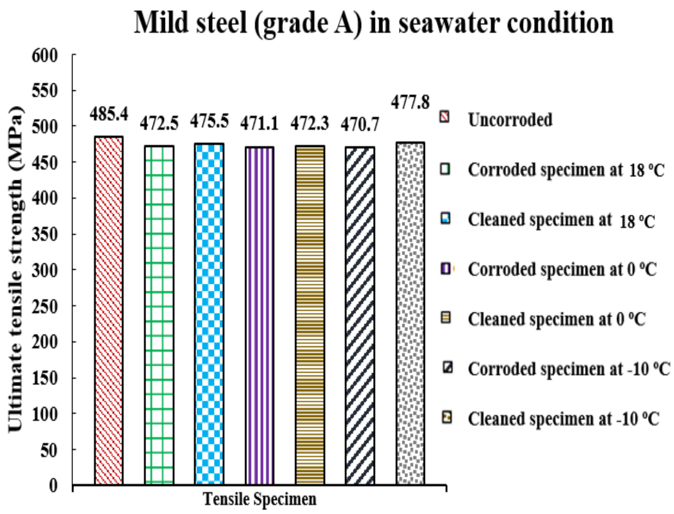


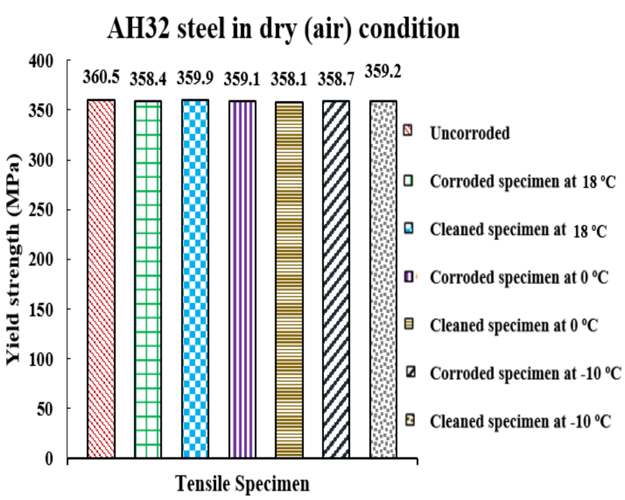
Figure 13. Comparison of the yield strength for mild steel (grade A) in (a) dry (air) condition, (b) freshwater condition and (c) seawater condition.



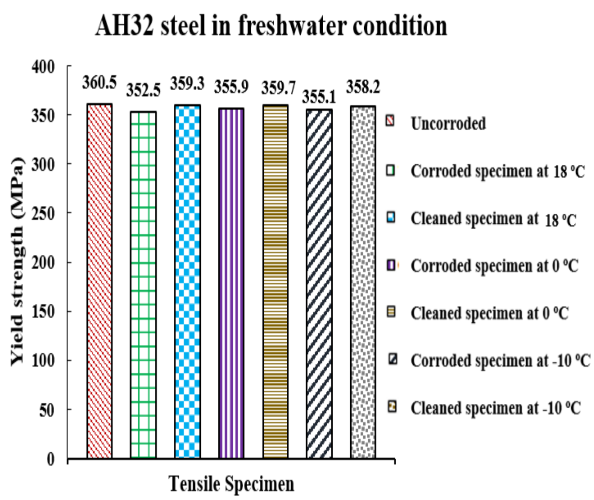


(c)

Figure 14. Comparison of the ultimate tensile strength for mild steel (grade A) in (a) dry (air) condition, (b) freshwater condition and (c) seawater condition.



(a)



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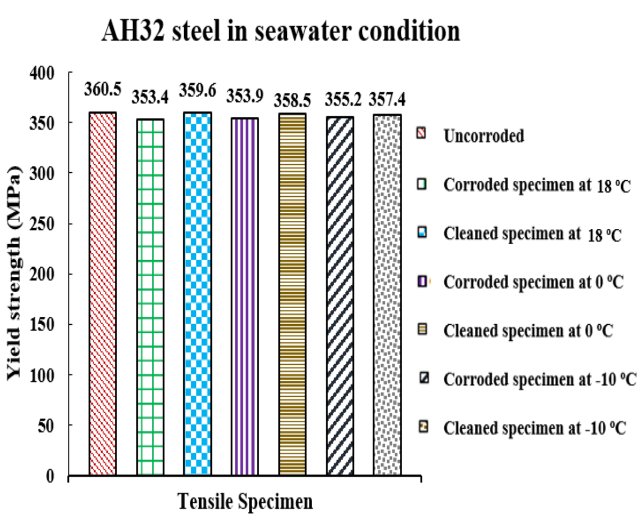


(c)

Figure 15. Comparison of the yield strength for AH32 steel in (a) dry (air) condition, (b) freshwater condition and (c) seawater condition.

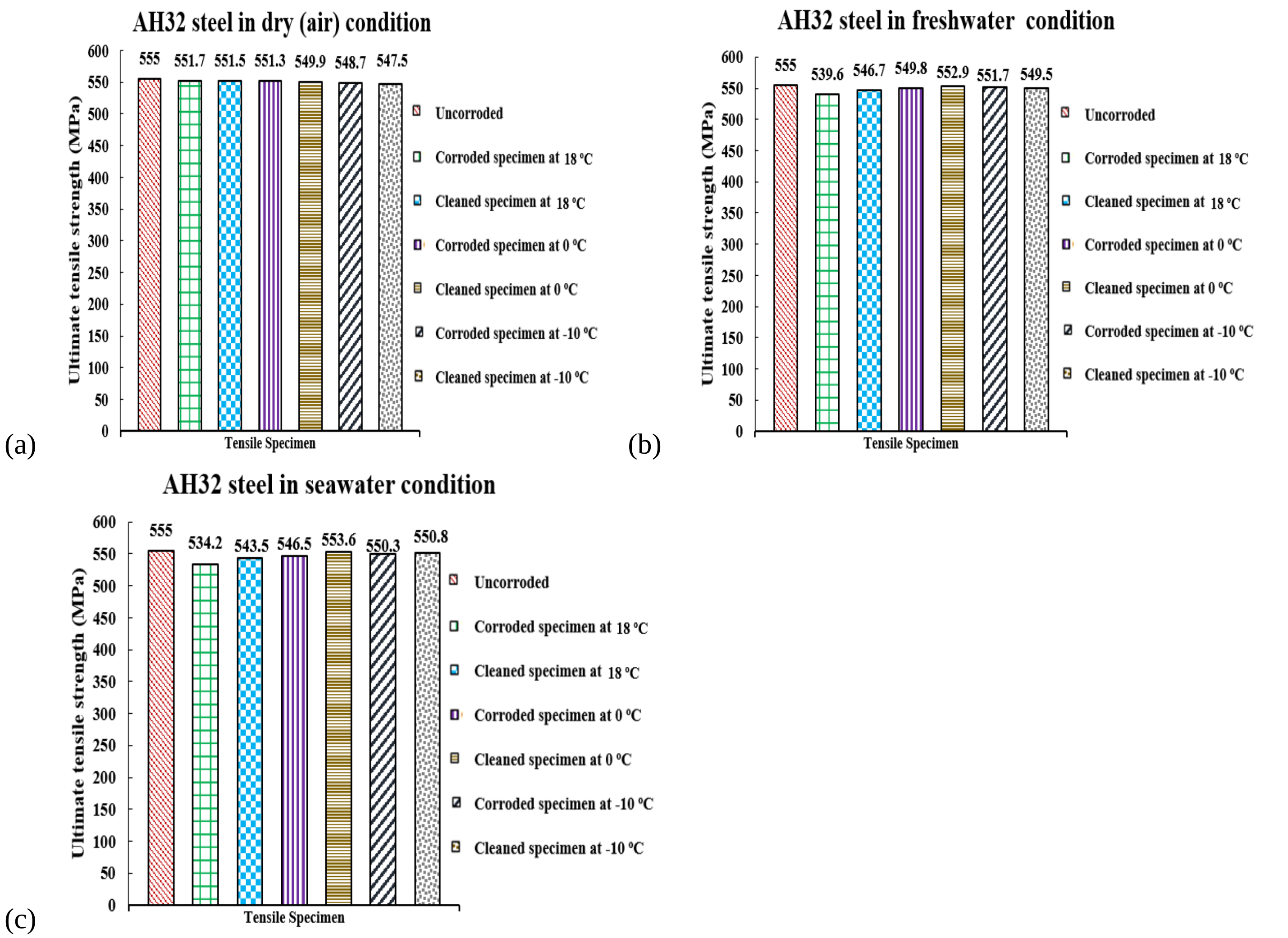
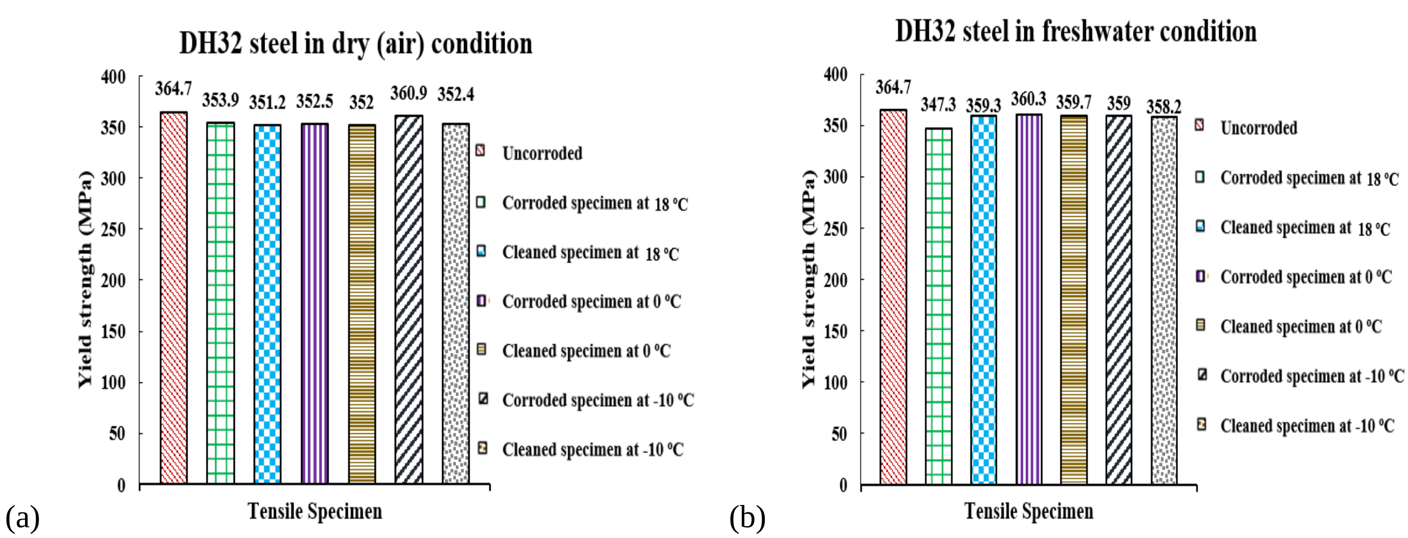
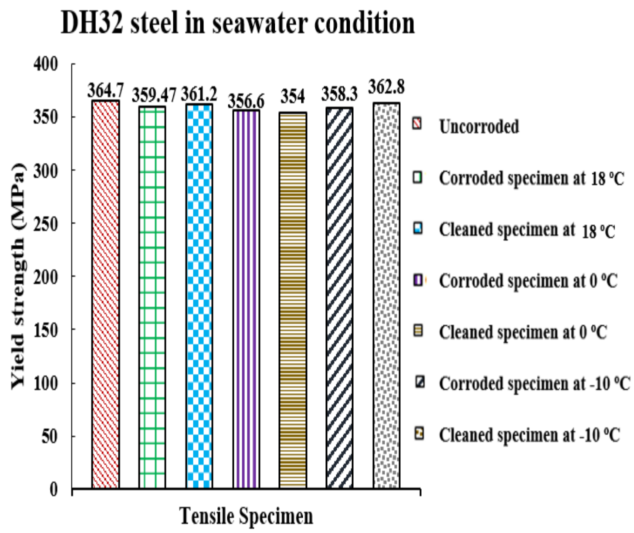


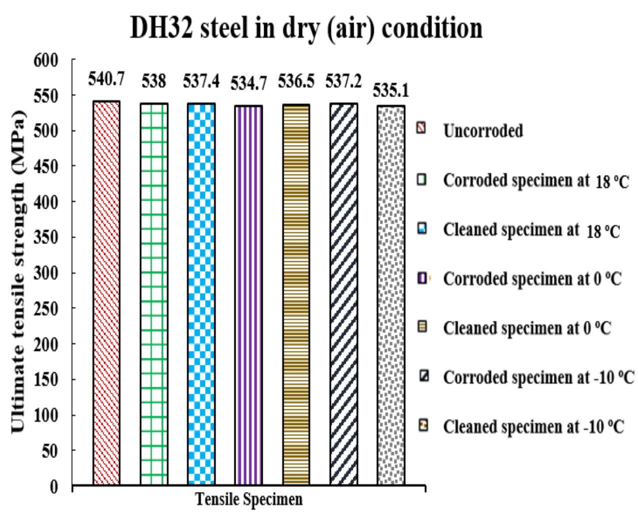
Figure 16. Comparison of the ultimate tensile strength for AH32 steel in (a) dry (air) condition, (b) freshwater condition and (c) seawater condition.



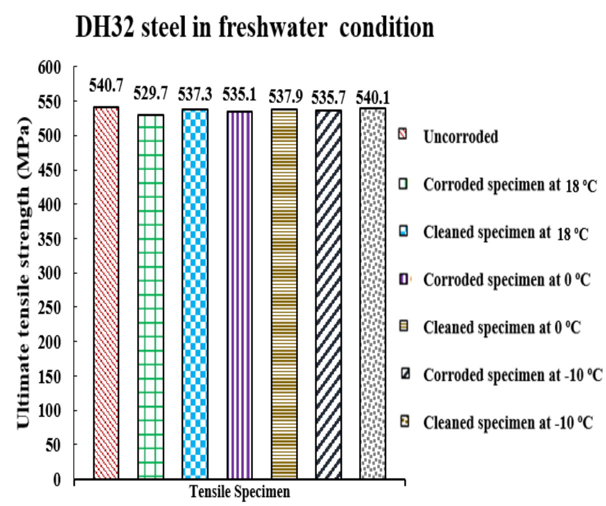


(c)

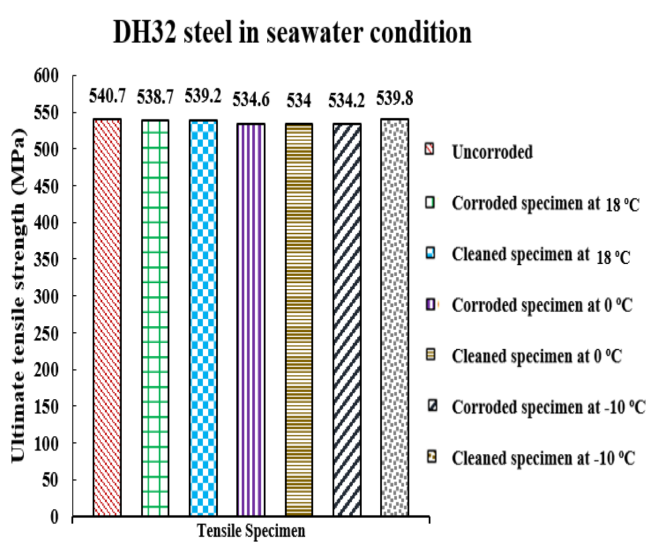
Figure 17. Comparison of the yield strength for DH32 steel in (a) dry (air) condition, (b) freshwater condition and (c) seawater condition.



(a)



(b)



(c)

Figure 18. Comparison of the ultimate tensile strength for DH32 steel in (a) dry (air) condition, (b) freshwater condition and (c) seawater condition.

6. Concluding Remarks

The aim of this paper was to experimentally examine the effects of corrosion wear on the chemical and mechanical properties of structural steels with the varying corrosive environments such as dry or water-immersed condition and cold temperature. Three kinds of structural steels with different grades were tested. In addition to dry (air) condition, two kinds of water-immersed conditions consisting of freshwater and seawater immersion were considered. The corrosion tests were continued for a period of 12 months. Waters were renewed every week to keep an average value of salinity and pH. The loss of mass, which could be converted to the reduction of equivalent plate thickness due to corrosion, was also measured at an interval of month. The rate of corrosion progress based on the test results was reported in a separate paper [25], while this paper focused on the effects of corrosion wear on the chemical and mechanical properties of structural steels. Based on the study, the following conclusions were drawn.

1. Two sets of test specimens for each material type were prepared for measuring the chemical properties before and after corrosion. The test specimen had a brick shape with a size of 20 mm × 20 mm × 6 mm. Chemical properties were measured using the glow discharge spectrometer method. The percentage composition of element Manganese was found to be the highest in all the three different grade steel specimens followed by Nickel and Silica. No significant variation in chemical composition was observed for corroded and non-corroded specimens. Although it is a common sense that chemical properties of steel are unaffected by corrosion. The intention of the paper was to develop clear evidence of such common sense by physical tests.
2. A total of sixteen specimens for mild steel (grade A), AH32 steel, and DH32 steel, i.e., three specimens for each type of material together with some spare specimens were prepared for measuring the mechanical properties before and after corrosion. The shape of test specimens was exactly the same as for tensile coupon tests as per the ASTM specifications. Two kinds of surface conditions in gauge area of tensile coupon test specimens after corrosion were studied, i.e., one (called corroded specimen) by removing corrosion rust only but perhaps with micro-pits on surface and the other (called cleaned specimen) by removing all micro-pits. Mechanical properties were measured from tensile coupon tests using universal tensile machine at a loading speed of 0.05 mm/s.
3. Among all the three types of materials in most of specimens, maximum loss in the yield and ultimate tensile strength was noticed at 18^{o}C compared to the intact specimen, and the effect of corrosion was reduced at colder temperature. However, some discrepancies were observed which may be accounted for the potential errors of tensile coupon testing along with the effects of geometric corrosion wear rather than the material properties themselves. The performance of DH32 steel was found to be relatively good in seawater immersion condition at room temperature (18^{o}C) in terms of the loss in yield and ultimate tensile strength, followed by mild steel and AH32 steel. In freshwater immersion condition at room temperature (18^{o}C), DH32 steel experienced 2% loss in the ultimate tensile strength followed by 2.8% in AH32 steel and 3.6% in mild steel. Moreover, in dry (air) condition at room temperature (18^{o}C), the loss in the ultimate tensile strength was maximum for mild steel (3.5%), followed by AH32 steel (0.6%) and DH32 steel (0.5%). In seawater immersion condition, maximum loss of yield strength in corroded specimens was observed in mild steel (grade A) at 0^{o}C by 2.75%, followed by 1.97% at 18^{o}C in AH32 steel, and 2.22 % at 0^{o}C in DH32 steel, respectively. In freshwater immersion condition, the yield strength of corroded

specimens at 18^{o}C was reduced by 5.4% in mild steel (grade A), followed by 4.77% in DH32 steel and 2.22% in AH32 steel.

5. In general, mechanical properties of cleaned specimen were better than corroded specimen with micro-pits. Yield strength and ultimate tensile strength of cleaned specimen were almost the same as corroded specimen. The fracture strain of cleaned specimen remained almost the same as corroded specimen in case of mild steel (grade A) specimens, while fracture strain for cleaned specimens was greater than corroded specimens by 1-9% in case of AH32 steel, and 10-20% greater than corroded specimens in case of DH32 steel. This may however be due to the effect of geometric wear (due to unsuccessful micro-pit cleaning) rather than material properties themselves.
6. In conclusion, the chemical properties of structural steel were not changed by corrosion at all. The mechanical properties of structural steels were also not affected by corrosion despite corrosive environments in terms of dry or water-immersed conditions and cold temperatures.

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