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RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

An Experimental Investigation of Mechanical Behavior of HY 80 Steel in Corrosive Mediums

HY 80 Çeliğinin Aşındırıcı Ortamlardaki Mekanik Davranışının Deneysel Olarak İncelenmesi

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Abstract

In this study, mechanical behavior of HY 80 steel in various mediums such as solutions of HCl, H_2SO_4 and NaOH has been investigated experimentally. The plate specimens, tensile specimens and V-notched specimens are immersed in solutions of HCl, H_2SO_4 and NaOH. Mass losses of immersed HY 80 flat plate specimens are measured after 1 week, 2 weeks and 4 weeks for each H_2SO_4, NaOH and HCl solutions to determine the aggressivity of the corrosive medium to surface of HY 80 steel. Also, tensile specimens and V-notched specimens are immersed for 1, 2 and 4 weeks to study on the effect of corrosive medium on fracture toughness and yielding behavior of HY 80 steels. The results show that however, yielding strength and ultimate tensile strength of HY 80 steel have reduced after immersed in acidic solutions of HCl and H_2SO_4, are stable after immersed in solution of NaOH. Furthermore, effect of acidic medium lower the fracture toughness of HY 80 steel.

Keywords: *HY 80 steel, corrosion, fracture, yield strength, elongation, impact*

Öz

Bu çalışmada, HY 80 çeliğinin, HCI, H_2SO_4 ve NaOH çözeltileri gibi çeşitli ortamlardaki mekanik davranışı deneysel olarak incelenmiştir. Plaka numuneleri, çekme numuneleri ve V çentikli numuneler, HCl, H_2SO_4 and NaOH çözeltilerine daldırılmıştır. HY 80 çeliğinin yüzeyinde korozif ortamın agresifliğini belirlemek için her bir H_2SO_4, NaOH ve HCl çözeltileri için daldırılan HY 80 yassı levha numunelerinin kütle kayıpları 1 hafta, 2 hafta ve 4 hafta sonra ölçülmüştür. Ayrıca, çekme numuneleri ve V çentikli numuneler, korozif ortamın HY 80 çeliklerinin kırılma tokluğu ve akma davranışı üzerindeki etkisini incelemek için 1, 2 ve 4 hafta boyunca daldırılmıştır. Sonuçlar, HY 80 çeliğinin akma dayanımı ve nihai çekme dayanımı, HCl ve H_2SO_4'ün asidik çözeltilerine daldırıldıktan sonra azaldığını göstermesine rağmen, NaOH çözeltisine daldırıldıktan sonra değişkenlik göstermemiştir. Ayrıca asidik ortamın etkisi HY 80 çeliğinin kırılma tokluğunu düşürmüştür.

Anahtar Kelimeler: *HY 80 çeliği, korozyon, kırılma, akma dayanımı, uzama, darbe*

1. Introduction

Corrosion is an electrochemical reaction causing to degrade material from the surface [1]. Corrosion phenomena is seen in many fields such as marine applications [2], industrial areas [3] and in environment [4, 5]. Corrosion is also formed in different types such as uniform [6] and pitting [5,7].

Tensile strength [8], yielding strength [9], crack propagation [10, 11, 12], fatigue life [13,14,15] are main mechanical properties that is affect by corrosion when the materials are exposed to aggressive mediums such as acidic [16] and saline [7, 17]. Corrosion effect on mechanical behavior of materials were studied experimentally [18] and/or numerically [19]. Also, materials work at operating conditions where both stress and corrosion are active [20, 21]. Many researches focused on the corrosion effect on mechanical character of materials such as steels [22], aluminum [23,24], copper alloys [25], zinc-magnesium alloys [4] and welded joints [26,27] at different mediums and conditions.

Rajput and Paik focused on 3 types of structural steels such as grade A mild steel, AH 32 steel and DH 32 steel. Tensile specimens were kept in seawater, freshwater and in the air at temperatures of 18° C, 0°C and -10°C during the 12 month-period. Yield strength and ultimate tensile strength of corroded specimens was not changed in dry and water-immersed solutions [28]. Rudomilova used dual phase steels to study the corrosion induced hydrogen effect with NaCl deposit in humid air. In the study, Rudomilova observed that dual phase steel demonstrated a reduction in properties of tensile strength and elongation because corrosion caused a decrease in cross-sectional area of the specimens and pitting was formed. On the other hand, Rudomilova demonstrated that hydrogen absorption for 27 days is inadequate to affect the mechanical properties [8]. Li et al. investigated corrosion effect on G250 mild steel used in bridge under stressed and non-stressed cases. The specimens are immersed in HCl solution having 2 different pH values such as 2.5 and 5, respectively. It is claimed that mass loss was drastically increased at stressed case for pH value of 2.5 and at stressed

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conditions there is a higher decrease in ultimate and yield strength of the steel than at non-stressed cases for both pH values in 28 day-tests [16]. Mishra analyzed the fatigue life of aluminum alloy 8011 after immersing in NaCl solutions having percentages of 3.5%, 4%, 4.5% and 5% for a week. Elongation of aluminum alloy 8011 is lowered from 16% to 10%. Failure occurred after $1.2x10^7$ cycles and $6x10^6$ cycles for uncorroded and corroded specimens for load of 4 kg and bending stress of 120.32MPa, respectively [29]. Garbatov et al. studied on box girder steel corroded in seawater. After a 20% degradation, corrosion effect becomes dominant on the mechanical character of the steel. It was found that there is nonlinear decrease in yield strength whereas linear decrease in tensile strength was observed [30]. Hamidah et al. used copper alloys in various solutions such as KOH, NaOH, NaCl and HCl to research corrosive effect of the mediums to mechanical properties. It was observed that increase in the concentration of electrolytes increases the corrosion rate. As the corrosion rate is lowered, the mean decrease in ultimate and yield strength lower for all solutions. It was also found that NaCl and HCl electrolytes are more dominant and effective on tensile strength and yield strength of copper rather than alkaline solutions [25].

HY-80 steel shows high strength, ductility, impact toughness [31]. Besides that, HY 80 has a great resistance in corrosive medium [32]. It is high strength steel to provide mechanical properties needed in many Navy fields, such as ship and submarine hulls [33]. Thus, the interested material in the work is chosen as HY-80 steel. The novelty of the study is that mechanical properties of HY 80 steel such as tensile strength, yielding strength, impact energy, fracture (rupture) elongation have not been investigated in corrosive mediums. HCl, H_2SO_4 and NaOH solutions have been prepared and the HY 80 steel specimens have been immersed in the solutions to determine the effect of aggressive mediums.

2. Materials and Methods

2.1. Material and Chemical Composition

HY 80 steel is a high yield steel and commonly used in fields of submarine. Chemical composition of HY 80 Steel is given table 1. As shown in Figure 1, Tensile and V-notched specimens are prepared according to TS EN ISO 6892-1 [34] and TS EN ISO 148-1 standards, respectively [35] and metal flat plates are manufactured to be used to measure the mass loss of HY 80 steel for 7, 14 and 28 days and all specimens immersed in alkaline and acidic solutions. For Charpy impact and tensile test, two V-notched specimen and tensile specimen were submerged for each period of 7, 14, 28 days and then, average of yield Charpy-impact test to compare the mechanical behavior for each medium in the strength value, ultimate tensile strength value, fracture elongation and fracture energy of specimens were found in tensile test and study. For mass loss calculations, three flat metals were used for 7,14 and 28 day-measurement in each solution. The tensile specimens were covered with two elastic resistant bands to avoid corrosion in solutions at regions where the grips of tensile test machine hold.

Table 1. Chemical Composition of HY 80 steel.

Element	C	Cr	Cu	Mn	Mo	Ni	P	Si	Ti	S	V
Content %	0.12-0.18	1.00-1.8	Max 0.25	0.10-0.40	0.20-0.60	2.00-3.25	Max 0.025	0.15-0.35	0.02	Max 0.025	0.03

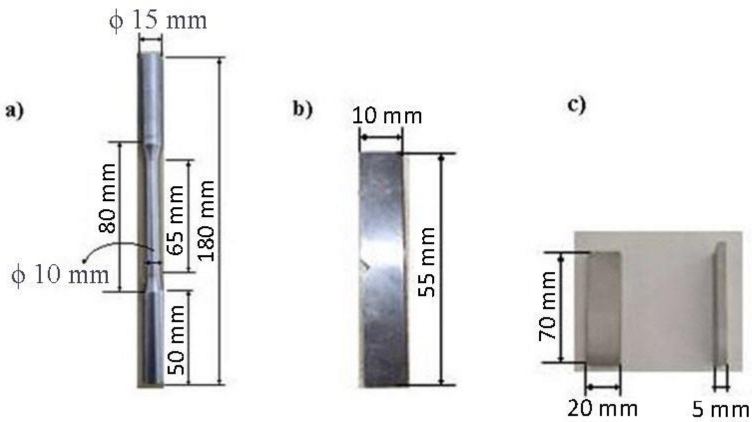

Figure 1. a) Tensile test specimen, b) Charpy-impact test specimen, c) flat plate

2.2. Solution Types and Preparation

To understand the corrosion effect on mass loss, mechanical behavior of HY 80 steel, the steel specimens were kept in different aggressive mediums. In the experiments, three different solutions such as sulfuric acid, hydrochloric acid, sodium hydroxide were prepared at different percentages. pH values of solutions measured by pH meter were given in Table 2.

Table 2. pH values of solutions

Solution Types	pH
Sulfuric Acid (H_2SO_4)	0.4
Hydrochloric Acid (HCl)	0.7
Sodium Hydroxide (NaOH)	13.7

Corrosion mechanism is a made up of oxygen reduction (Eq. 1 and Eq. 2) and hydrogen evolution reaction (Eq. 3 and Eq. 4) [36, 37].

Oxygen Reduction Reaction:

$$\frac{1}{2}O_2 + 2H_3O^+ + 2e \rightarrow 3H_2O \text{ Acid} \quad (1)$$

$$\frac{1}{2}O_2 + H_2O + 2e \rightarrow 2OH^- \text{ Neutral Alkaline} \quad (2)$$

Hydrogen Evolution Reaction:

$$H_3O^+ + e \rightarrow \frac{1}{2}H_2 + H_2O \text{ acid} \quad (3)$$

$$H_2O + e \rightarrow \frac{1}{2}H_2 + OH^- \text{ Neutral Alkaline} \quad (4)$$

3. Results and Discussion

3.1. Mass Loss Calculation of HY 80 steels

The mass loss was calculated by equation 5,

$$\Delta M = M_{ini} - M_{fin} \quad (5)$$

Where M_{ini} (g) the mass at the beginning before it is corroded. M_{fin} (g) is the measured final mass after immersed in aggressive medium.

Submerged HY 80 plates in H_2SO_4 solutions loss highest mass in all. There is a quite increase in mass loss during 28 days for H_2SO_4 solution. Mass loss in percentage reaches to approximately 16% of initial mass for 28 days. Mass loss in submerged HY 80 plates in HCl solutions slightly increases to approximately 2.5 % of initial mass. The mass loss for NaOH solution is too low, almost zero as depicted in Figure 2. So, because of corrosion mechanism, material loss increased in different aggressive solutions in a certain period.

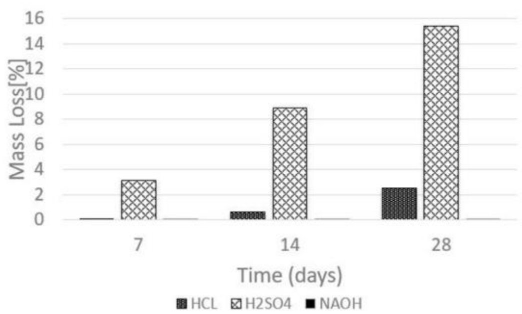

Figure 2. Mass loss of HY 80 plate steel

3.2. Tensile Test of HY 80 Steels

In an engineering tension test, the engineering stress and strain are expressed as σ_{eng} and ε_{eng} respectively, are calculated by measuring load and deflection using the original specimens having a cross-sectional area of A_i and a length of L_i as written in Eqs. 6 and 7.

$$\sigma_{eng} = \frac{F}{A_i} \quad (6)$$

$$\varepsilon_{eng} = \frac{L-L_i}{L_i} \quad (7)$$

To calculate true tensile stress, A is denoted as real cross-sectional area and continuously reduces during test until the specimens is fractured and the elongation is measured instantaneously to have true stress-strain curve [38]. The true tensile stress and strain are expressed in Eqs. 8 and 9.

$$\sigma_T = \frac{F}{A} = \frac{F}{A_0}(1+\varepsilon_e) = \sigma_e(1+\varepsilon_e) \quad (8)$$

$$\varepsilon_T = \int_{L_0}^{L}\frac{1}{L}dL = ln\frac{L}{L_0} = \ln(1+\varepsilon_e) \quad (9)$$

3.3. Effect of Corrosive Mediums on Yielding Strength, Ultimate Strength, Rupture Elongation and Impact Energy of HY 80 steels

HY 80 tensile samples prepared in different corrosive environments are tested. Average yield strength, ultimate strength and fracture elongation of non-corroded specimen are founded as 630.2 MPa, 765.5MPa and 27.5 % respectively as depicted in Figure 3, 5 and 7. The yield and ultimate strength slightly decrease during 28 day-period. Yield strength drops to 618.1MPa, 606.5 MPa and 619.9 MPa for 7 day-test in HCl, H_2SO_4 and NaOH solutions respectively and 573.9MPa, 592.4MPa and 629.9 MPa for 14 day-test in HCl, H_2SO_4 and NaOH solutions respectively as illustrated in Figure 3. Ultimate strength lowers to 746.7 MPa, 714.2 MPa and 733.4 MPa for 7 day-test in HCl, H_2SO_4 and NaOH solutions respectively and 730.6MPa, 711.7 MPa for 14 day-test in HCl, H_2SO_4 respectively as shown in Figure 5.

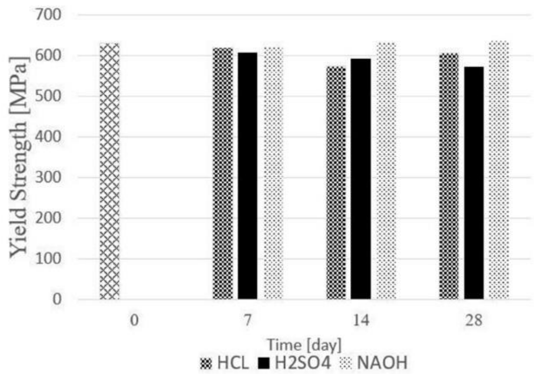

Figure 3. Yield strength of HY 80 steel immersed in different solutions

HCl and H_2SO_4 solutions are more dominant in reduction of yield and ultimate strength. NaOH solution is not effective to lower the yield and ultimate strength. Reduction in yield and ultimate strength reaches up to 9.28 % and 14.11 % for aggressive medium of H_2SO_4 solution respectively as illustrated in Figure 4 and 6. Reduction in yield strength of HY 80 steel immersed in solution of H_2SO_4 shows a decreasingly increase character as depicted in Figure 4.

For HY 80 steel samples immersed in NaOH preserve the yield strength as shown in Figure 4. It is seen in Figure 4 that HCl solution causes reduction in yield strength of immersed HY 80 steels.

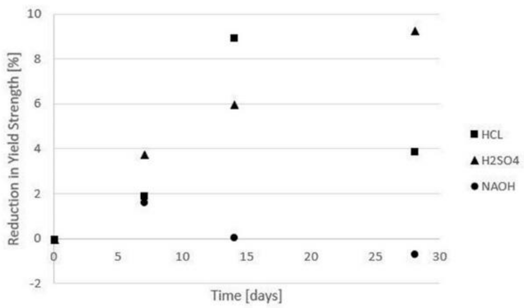

Figure 4. Yield strength reduction versus time

As shown in Figure 5 and 6, ultimate strength of immersed HY 80 steel samples in solution of HCl is decreased, the reduction in ultimate strength shows a decreasingly increase character.

Besides, H_2SO_4 solution effect ultimate strength of immersed samples and decrease the strength of the samples in 28 day-test period drastically as illustrated in Figure 6.

Ultimate strength of immersed HY 80 steel samples in solution of NaOH does not show a remarkable change as shown in Figure 5 and 6.

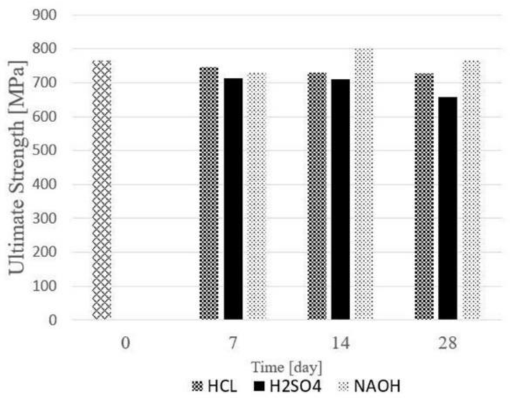

Figure 5. Ultimate strength of HY 80 steel immersed in different solutions

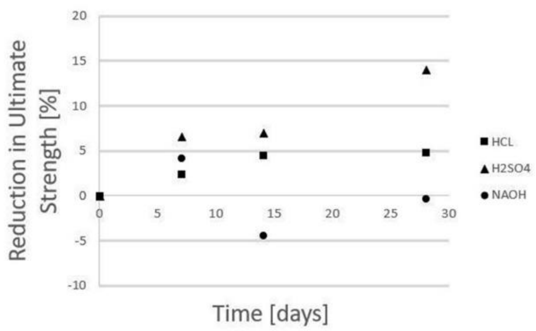

Figure 6. Ultimate Strength Reduction versus time

Especially, by the help of mass losing of specimens yield and ultimate strength of HY 80 steel have a tendency to reduce in acidic environment.

Fracture elongation defines the highest percentage permanent extension amount that occurs in the length of the tensile sample. This shows the ductility of the material. The more ductile the material, the more the deformation will occur [39].

Furthermore, fracture elongation is 26.2 %, 26.9 % and 26.4 % for 7 day-test in HCl, H_2SO_4 and NaOH solutions respectively, Fracture elongation drops to 26%, 26.2% and 24.5 % for 14 day-test in HCl, H_2SO_4 and NaOH solutions respectively and 23.85%, 25.7% and 23.8 % for 28 day-test in HCl, H_2SO_4 and NaOH solutions respectively as illustrated in Figure 7. Thus, HY 80 steel becomes less ductile as being submerged in corrosive mediums where corrosion reactions in Eqs. 3 and 4 take places. Also, corrosive medium affects the fracture toughness of HY 80 steel. HCl solution lowers impact energy to 220.5 J and 210.5 for 7 day-test and 14 day-test as depicted in Figure 8. Also, H_2SO_4 aggressive medium reduce impact energy to 210 J and 197 J for 7 day-test and 14 day-test. Furthermore, NaOH medium reduce impact energy to 212.5 J and 207 J for 7 day-test and 14 day-test. As shown in Figure 9, For all immersed HY 80 steel samples, the reduction in impact energy of HY 80 steels shows a decreasingly increase character in solutions of HCl, H_2SO_4 and NaOH. H_2SO_4 solution is the most effective solution in all to reduce the impact energy of HY 80 steel. Maximum reduction in impact energy was observed for 14 day-tested specimens in H_2SO_4 solution as depicted in Figure 9. So, the impact strength of HY 80 steel lowered due to H evolution reactions realized in acidic and salty solutions in Eqs. 3 and 4.

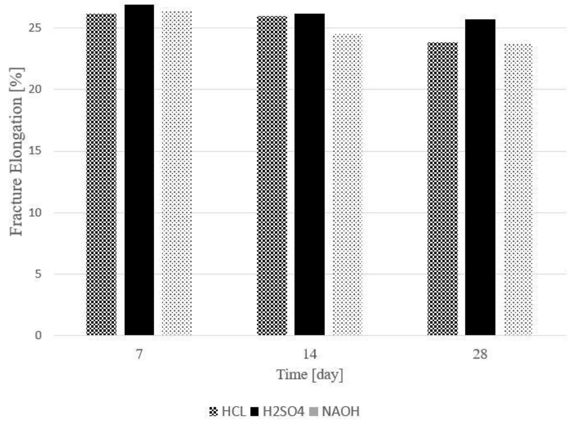

Figure 7. Fracture Elongation of HY 80 steel immersed in different solutions

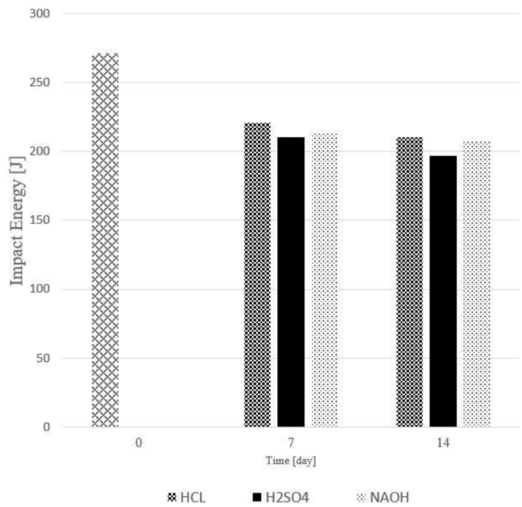

Figure 8. Impact Energy of V-notched HY 80 steel

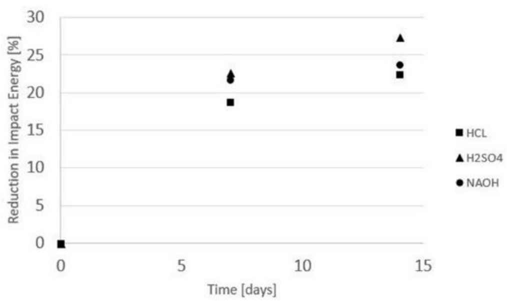

Figure 9. Impact energy reduction versus time

3.4. Fracture surface of specimens after Charpy-Impact Test

To characterize rupture surface 1 week-fractured V-notched and 4 week-fracture V-notched specimens were photographed for HCl, H_2SO_4 and NaOH solutions as shown in Figure 10. It is observed that the bright field on the fractured surface slightly increases when 1-week corroded fractured V-notched specimens is compared to 4-week corroded fractured V-notched specimens for H_2SO_4 solutions as depicted in Figure 10.

3.5. Fracture surface of specimens after Tensile Test

To investigate the effect of corrosive mediums on the fractured surface of tensile specimens, the fractured surface of specimens are photographed in high definition and compared to each other. For non-corroded HY 80 specimens, the fractured surface shows ductile behaviour and have a cup and cone geometry as depicted in Figure 11. For HCl solutions, the cup and cone geometry of the fractured specimens is detetoriated after 28-day submerge. Also, especially, brittle mechanism is dominant on the fractured surface of HY 80 specimens in H_2SO_4 solutions after submerged in 28 days as shown in Figure 11.

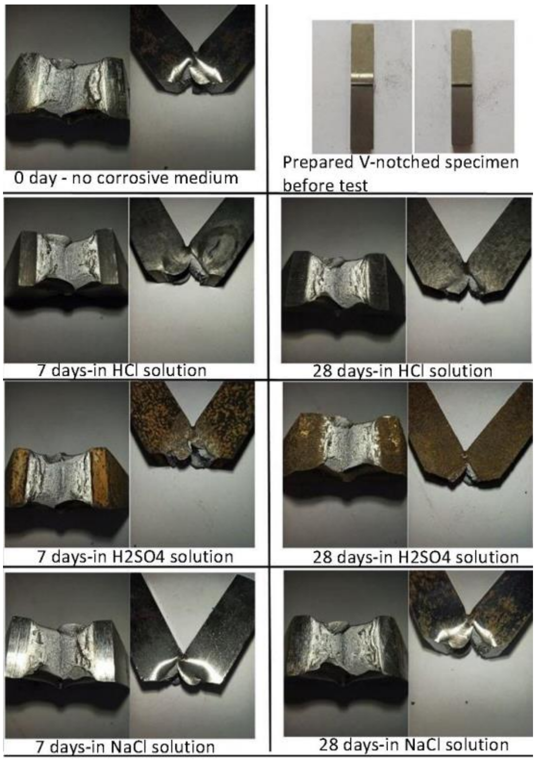

Figure 10. Fractured surface of V-notch Specimens

Figure 11. Fractured surface of tensile specimens

4. Conclusions

The specimens were immersed in acidic, alkaline solutions and mechanical properties such as yielding behavior and fracture toughness of HY 80 steels were investigated by applying tensile test, Charpy-impact test, measuring mass loss of HY 80 steel specimens. In the work, the yield strength of HY 80 steel reduces by 3.88 %, where as in the study of Li et al. there is a reduction of 4.08 % in yield strength of 250 mild steel [16]. In addition, the ultimate strength of aluminum alloy 8011 in NaCl solution reduces by 4.39% in the study of Mishra et al [29] while 4.87 % reduction was observed in the study for HY 80 steel for 28 days' immersion.

There was a 9.29 % decrease in fracture toughness of Q235 steel in soil solution for a 90 days' immersion period in the work of Hou et al. [9] while in the study for the case of immersion of HY 80 steel in H_2SO_4 solution, there is 27.44 % reduction in impact energy.

When the fracture surfaces are examined, a matte surface is observed in the 2-week-old sample, and the amount of bright fracture surface is higher in the 4-week-old sample. In the HCl solution, the fracture surfaces are lipped. Ductile fracture has occurred. Fracture surfaces were observed to be similar to each other at 2 and 4 weeks of age. Fracture toughness energies were close to each other for 1 and 2 week immersed notched samples kept in NaOH solution. In the immersion process, hydrogen atoms were allowed to enter the sample. A slight decrease was observed in the fracture toughness of the samples in HCl and H_2SO_4 solutions. It was observed that the ductility of the samples in the immersed HCl and H_2SO_4 solutions decreased and the brittleness increased. The increase in brittleness causes the samples to break and damage suddenly without showing any symptoms. It was observed that the effect of corrosion on yield and tensile strength was limited, on the other hand, it affected the decrease in material ductility.

The results show that in aggressive environment such as H_2SO_4 and acidic medium of HCl, there is a certain corrosive effect in reduction of yield, ultimate strength and impact energy of HY 80 steel. So, much more resistive coatings can be applied on HY80 steel to minimize the corrosive effect on yield, ultimate strength and impact energy. However, in salty medium, for HY 80 steel, there is no notable effect in reduction of yield, ultimate strength, NaCl solution has an effect in reduction of impact energy of HY 80 samples. Hence, in short term periods, HY 80 preserve its stability against corrosion in terms of yield and ultimate strength at salty medium, but for long term periods, it may require to be coated by an alternative resistive material.

In future studies, the corrosion behavior under stress can be investigated. With stress corrosion, many more hydrogen atoms can be allowed to penetrate the part during the same period.

Ethics committee approval and conflicts of interest

The authors declare no need for an ethics committee approval and no conflict of interest in this paper.

Author Contribution Statement

Buğra Yılmaz did tests.

Ergin Kosa did literature investigation, contributed to identification of conceptualization and methodology, drafting of article and critical review of content and final approval.

Şenol Durmuşoğlu did material preparation.

Nomenclature

F = force (N)

$\mathrm{A_i}$ = initial cross sectional area ($\mathrm{m^{-1}}$)

$\mathrm{A_o}$ = original cross sectional area ($\mathrm{m^{-1}}$)

σ_{eng} = engineering stress (N $\mathrm{m^{-2}}$)

$\varepsilon_{\mathrm{eng}}$ = engineering strain (mm $\mathrm{mm^{-1}}$)

σ_{T} = true stress (N $\mathrm{m^{-2}}$)

ε_{T} = true strain (mm $\mathrm{mm^{-1}}$)

$\mathrm{L_i}$ = initial length (m)

$\mathrm{L_o}$ = original length (m)

$\mathrm{M_{ini}}$ = initial mass (g)

$\mathrm{M_{fin}}$ = final mass (g)

$\Delta\mathrm{m}$ = mass difference (g)

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