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A Comparative Study on the Corrosion Behavior of a Mild Steel in Several Beverages and Water

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ABSTRACT

There are many beverages in the market. People usually choose the beverage depending on its flavor, but barely have the knowledge about its corrosivity. A systematic study was carried out to investigate the corrosion behavior of X-60 mild steel in several beverages (Coca Cola, Laoshan Cola, Qingdao beer, Kvass, Laoshan Oldenlanidawater, and Laoshan Soda) in opened and closed systems by weight loss measurement at room temperature and atmosphere pressure. The comparison for each beverage in opened and closed systems was made to understand the effect of releasing CO_2 on the corrosivity. The corrosivity of tap water in the opened system was also investigated to compare with other beverages. The initial pH value and change of pH with test time was measured. The results showed all beverages tested in this study was acidic while tap water was alkaline. Compared to the opened system, each beverage had a lower corrosion rate in the closed system except for Kvass. The corrosivity of beverages and tap water decreased in the order of Kvass, Coca Cola, Laoshan Cola, Laoshan Oldenlandianwater, Laoshan soda, tap water, and Qingdao beer.

Introduction

There are many drinks, such as water, Coca Cola, Laoshan Cola, Qingdao beer, Kvass, Oldenlanidawater, and Laoshan Soda. You may prefer one of them because it tastes better than others. Coca Cola and Laoshan Cola are carbonated beverages. Qingdao beer and Kvass are usually considered as liquid bread and a kind of neutral beverage. Water is also considered as a kind of neutral drink. It is widely accepted that Laoshan Soda and Oldenlanidawater are alkaline beverages. Many kinds of additives are added to water to make beverages and create the special tastes. For example, Sodium bicarbonate ($NaHCO_3$) is added to water to make Laoshan soda. Oldenlandia extract, $NaHCO_3$ and potassium chloride (KCl) are added to water to produce Laoshan Oldenlandiawater. which is a kind of flavored beverage.

Kids are usually told by their parents to drink water, but not too much Cola because it is carbonated beverage.

Dissolved CO_2 in carbonated beverages creates a low pH environment, therefore it is corrosive to the kid's teeth[1]. However, the corrosivity of other beverages are seldom mentioned. Does it mean that other beverages are less corrosive than carbonated beverages?

Plastic and aluminum packaging has made the modern supply chain efficient with consumer being supplied with bottled and canned beverages from different regions of the world [2,3]. When the manufacturers make beverages

(Coca Cola, Laoshan Cola, Qingdao beer, Kvass, Laoshan Soda, and Oldenlanidawater), carbon dioxide (CO_2) is added before the bottles or cans are sealed. This is the reason why large amounts of CO_2 microbubbles are released when you open the bottles or cans of these beverages. CO_2 is a weak acidic gas. When CO_2 dissolves into beverage, carbonic acid (H_2CO_3) will form which leads to the decrease in pH value. This process makes beverages become more corrosive. It is believed the lower the pH of the beverage is, the more corrosive the beverage will be. As carbonated beverages, Coca Cola and Laoshan Cola should have a pH value less than 7. It is commonly accepted that tap water, Qingdao beer, and Kvass have a pH of around 7. As alkaline beverages, the pH value of Laoshan Soda and Oldenlanidawater should be over 7. The fact the beverages are acidic, neutral, or alkaline is based on the ideal state of storage. In some case, beverages are opened without being finished, which causes CO_2 to be released. The opened and closed beverages may have different corrosivity.

Chen et al.[3] investigated the release of microplastics and nanoplastics from plastic bottles for chilled carbonated beverages which may pose a higher potential to harm human health. Soares et al.[4] studied interaction between aluminium cans and citric acid beverages and found that the failure of aluminium packaging can cause high concentration of aluminium in the beverage due to corrosion. Duffó and Farina[5] performed a systematic study of the effect of several beverages (alcoholic drinks, natural and artificial fruit juices, vinegar, soft drinks, milk) on the corrosion behaviour of an aluminum–bronze dental alloy. They found artificial orange juice is the most aggressive beverage and its corrosion rate was one order of magnitude higher than artificial saliva. However, the corrosivity of different beverages and drinks and their effect on human body has not been extensively addressed.

The objective of this work is directed towards investigating the corrosivity of several beverages and tap water for X-60 mild steel in the opened and closed systems through long-term corrosion tests. Tap water was used as a baseline to compare the corrosivity of different beverages in the opened system. The corrosion behavior of each beverage in the opened and closed systems was also compared to understand the effect of the injected CO_2 on the corrosion.

It is worth noting that the results in this study only represents the corrosivity of the beverage itself. It is well known that beverages are diluted by other substances in the stomach, and gradually absorbed and digested by the human digestive system in about four to six hours. Therefore, the results may not represent its true harm to the human body. It is hoped that this work will not affect beverage sales or consumer choices.

Experimental Procedures

Materials and Preparation

The material used for testing was X-60 mild steel. The size of each specimen was 50*10*3 (mm) with an exposed surface area of 13.6 cm^2. The specimens were successively polished with SiC papers up to # 600, and then rinsed with isopropanol. Tap water and six types of beverages including: Coca Cola, Laoshan Cola, Qingdao beer, Kvass, Laoshan Soda, and Oldenlanidawater, were used as test solutions in this study. Tap water, Laoshan Cola, Qingdao beer, Laoshan Soda, and Oldenlanidawater, were produced in Qingdao, China. Kvass was a Russian flavored beverage produced by Wahaha company. The average general corrosion rates were determined by weight-loss measurements. The initial and final weight of the specimens were measured with an electronic balance with a precision of 0.1mg. The corrosion rates were calculated by using the following equation:

$$CR=\frac{87600\Delta m}{\rho AT}$$

Where CR is the corrosion rate of the sample in mm/year, Δm is the weight loss in grams, ρ is the density of the sample in g/cm^3, A is the exposed area in cm^2, and T is the immersion time in hours.

After the experiments, coupons were immediately retrieved, rinsed, dried, and then stored in a desiccator. ASTM G1-03 (2009) standard procedure was followed to remove the corrosion products by Clarke solution, which was composed of 1000 mL HCl, 20 g Sb_2O_3 and 50 g $SnCl_2$. All tests were performed at room temperature and atmosphere pressure. After the tests, the specimens were rinsed with water and then isopropanol. Surface morphology of coupons was characterized by SEM before and after the corrosion product was removed. 3D profilometer (IFM) was performed to qualify pitting corrosion after the corrosion product was removed.

Testing Procedures

All of experiments were performed in 500 mL clear glass bottles. 400 mL beverage or tap water were added to each container. One coupon was immersed to the tested solution by a no-conducting white string in each test.

Four serials of tests are included in this study. In the first serial, tap water was tested in the opened system for 382 hours to compare its corrosivity with other beverages. In the second serial of tests, Laoshan Cola and Coca Cola were tested in the opened and closed systems for 382 hours. In the third serial of tests, Kvass and Qingdao beer were tested in the opened and closed systems for 336 hours. In the fourth serial of tests, Laoshan soda and Laoshan oldenlandianwater were tested in the opened and closed systems for 1148 hours. In each closed system, a plastic stopper was applied on the lid of the container to prevent the release of CO_2 from beverage. In each opened system, CO_2 can be gradually released from beverage with time. The pH value was measured during the test occasionally.

Results and Discussion

Corrosion Behavior in the Tap Water

The general corrosion rates determined by mass loss measurement for X-60 sample exposed to tap water was 0.15 mm/y. Figure 1 is the variation of pH with testing time. It is surprising that the initial pH value of tap water in Qingdao was around 7.7, which means it was not neutral, but alkaline. The pH value of tap water decreased with testing time and eventually reached 7 after 382 hours. The corrosivity of tap water was highly related to the water quality[6,7]. Oxygen, anions, and cations dissolved in tap water could affect its corrosivity.

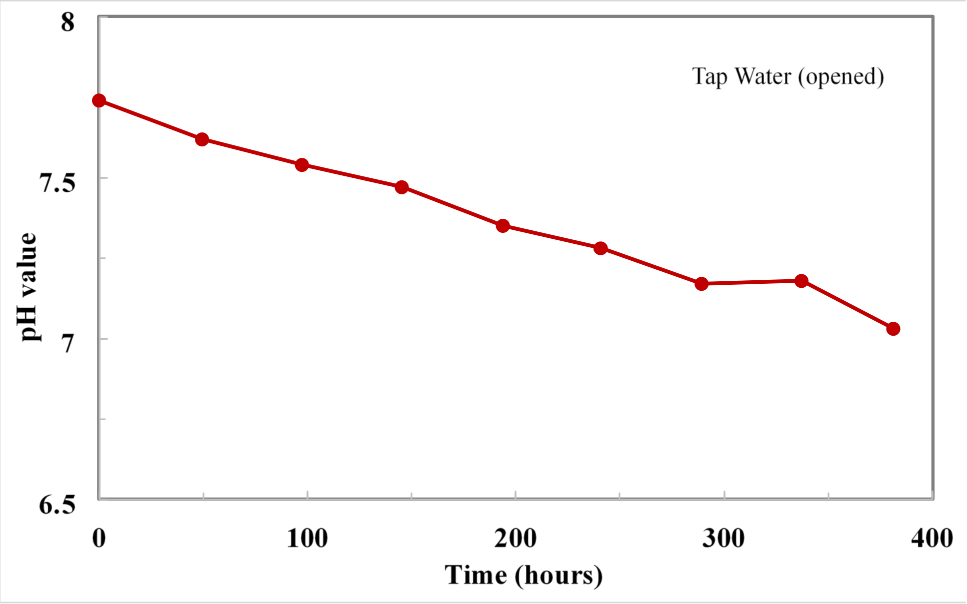
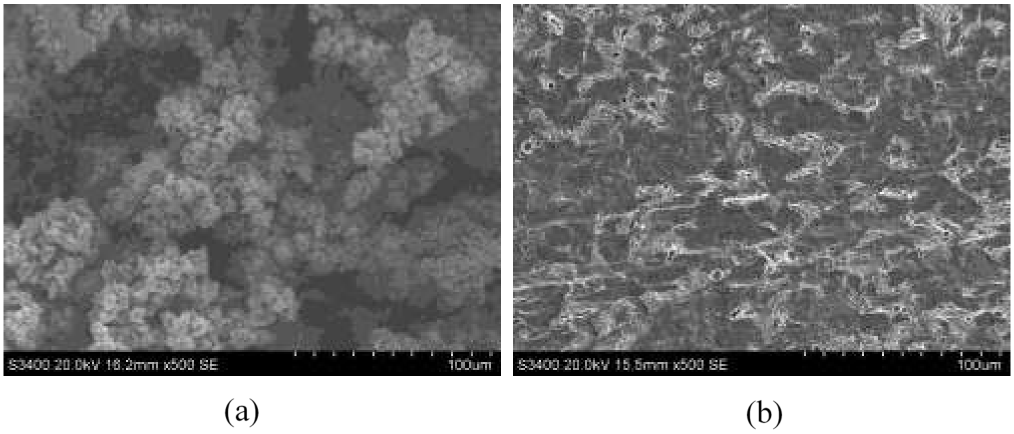


Figure 1. The change of pH value as a function of testing time in the tap water

Figure 2 shows SEM morphologies of X-60 mild steel exposed to tap water for 382 hours with and without the corrosion product. Dendric and porous corrosion product accumulated on the metal surface. After removing the corrosion product, serious general corrosion as well as pitting corrosion was evident.



(a)

(b)

Figure 2. SEM morphologies of X-60 mild steel exposed to tap water for 382 hours with (a) and without (b) corrosion product

Corrosion Behavior in the Laoshan Cola and Coca Cola

Figure 3 presents the change of pH value with time for Laoshan Cola, and Coca Cola in the opened and closed systems. The initial pH value of Laoshan Cola and Coca Cola were 3.74 and 3.58, respectively. It suggests that both Laoshan Cola and Coca Cola are acidic beverages. The pH value of Coca cola was higher than that of Laoshan Cola during the testing time in both systems. The pH value of Laoshan cola in both systems were nearly identical at the whole testing time. The pH value of Laoshan Cola in both systems decreased in the first

150 hours to around 3.23.3, and then gradually increased over time to reach 3.77 and 3.63. The pH value of Coca Cola in the opened and closed systems both gradually increased in the first 50 hours to 4.01 and 4.38, and then decreased over time to reach 4.09 and 3.85. In the first 200 hours, the pH value of closed system of Coca Cola was slightly higher than that in the opened system.

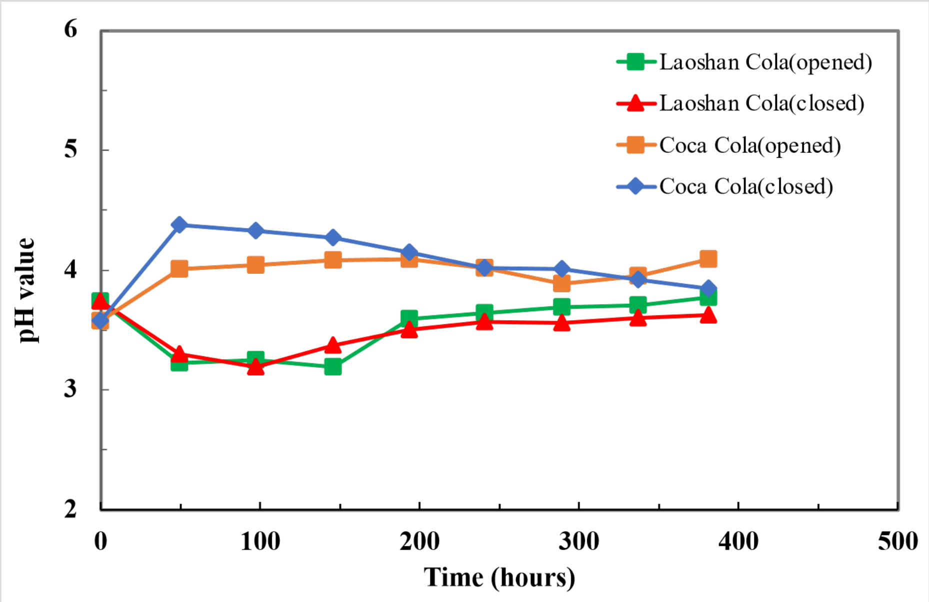


Figure 3. The variation of pH value during the testing time for Laoshan Cola, and Coca Cola in the opened and closed systems

Figure 4 presents the general corrosion rate of Laoshan Cola, and Coca Cola in the opened and closed systems. Coca Cola had higher corrosion rate than Laoshan Cola in both systems. Both Laoshan Cola and Coca Cola had higher corrosion rate in the opened system than closed system. CO_2 was released from Laoshan Cola and Coca Cola, and oxygen in the air dissolved into both beverages in the opened systems, which created a different corrosive environment from the closed system. Therefore, a higher corrosion rate was obtained in the opened system for both beverages.

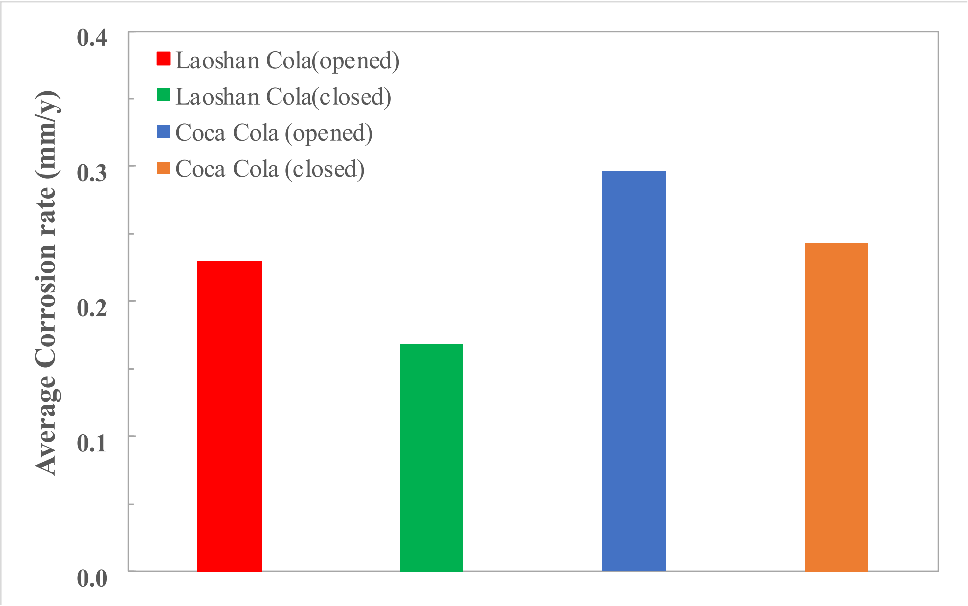
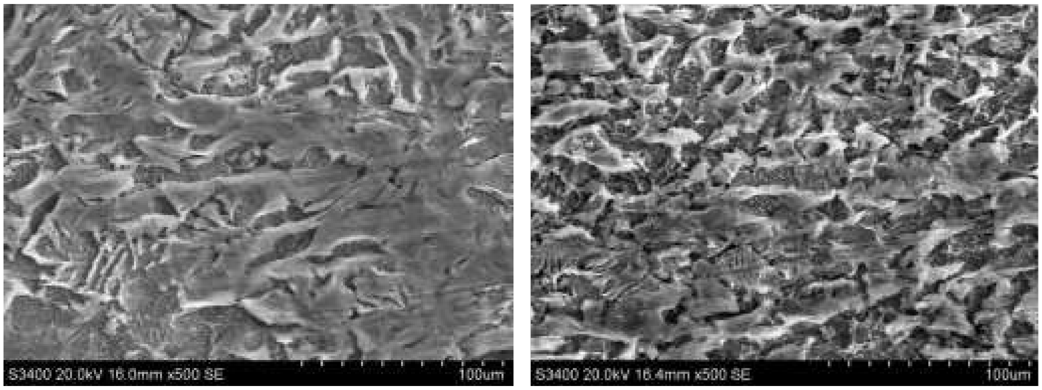
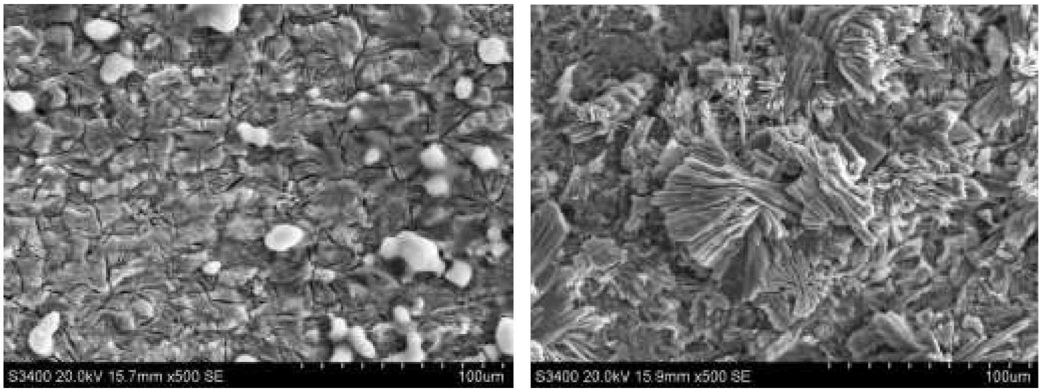


Figure 4. Average corrosion rates of X-60 mild steel exposed to Laoshan Cola and Coca Cola in both opened and closed systems

Figure 5 shows SEM morphologies of X-60 mild steel exposed to Laoshan Cola, and Coca Cola in the opened and closed systems for 382 hours with the corrosion product. Two layers of corrosion products were found on the coupon surface in Laoshan Cola for both opened and closed systems, where the outer layer of corrosion product was porous flake shaped. Mushroom like corrosion product and stacked formed corrosion product was seen in Coca Cola for opened system and closed system, respectively. Compared to Coca Cola, a lower pH value was observed in Figure 3, but a lower average corrosion rate was seen in Figure 4 for Laoshan Cola. This may be related to the protection ability of the corrosion product in Figure 5. The two layers of corrosion product, especially the inner layer in Laoshan cola can provide a better protection for metal corrosion.



(a) (b)

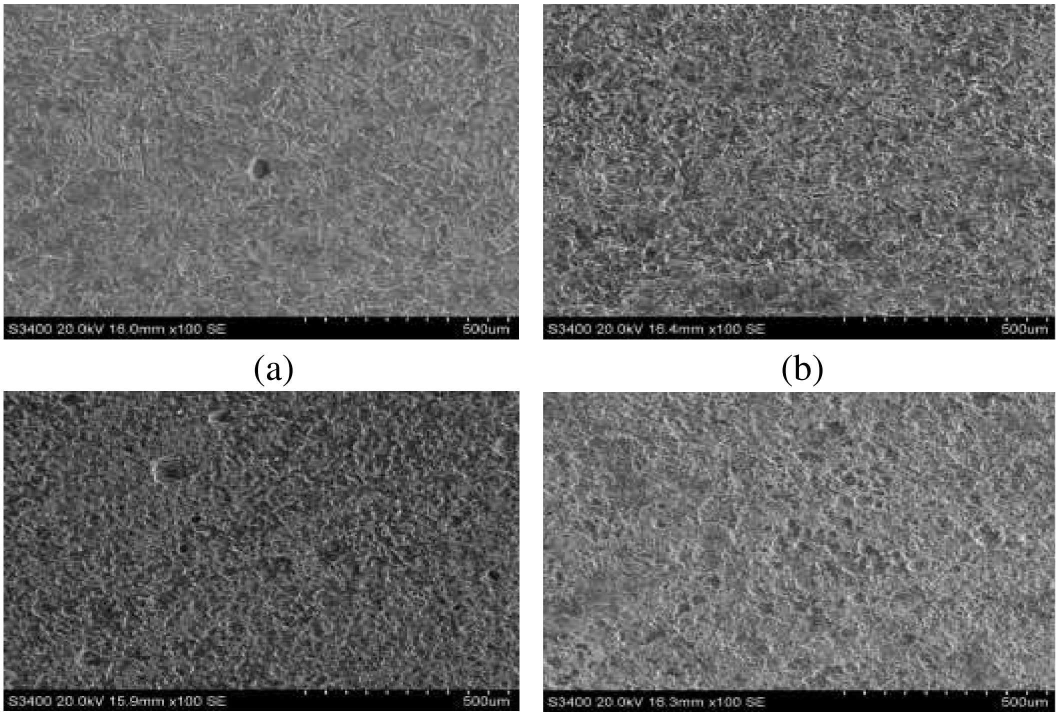


(c) (d)

Figure 5. SEM images of the X-60 mild steel coupons exposed to different beverages ((a) Laoshan Cola in the opened system, (b) Laoshan in the closed system, (c) Coca Cola in the opened system, (d) Coca Cola in the closed system)

Figure 6 presents SEM morphologies of X-60 mild steel exposed to Laoshan Cola and Coca Cola in the opened and closed systems for 382 hours without the corrosion product. Serious corrosion attack and pits were present on each coupon.

Therefore, X-60 mild steel experienced serious general corrosion and pitting corrosion in both Laoshan Cola and Coca Cola for the opened and closed systems. The general corrosion rates for both beverages in opened system were higher than that in closed system.



(a) (b)

(c) (d)

Figure 6. SEM images of the X-60 mild steel coupons exposed to different beverages ((a) Laoshan Cola in the opened system, (b) Laoshan Cola in the closed system, (c) Coca Cola in the opened system, (d) Coca Cola in the closed system)

Corrosion Behavior in the Kvass and Qingdao Beer

Figure 7 shows the change of pH value with time for Kvass and Qingdao beer in the opened and closed systems. The initial pH value of Kvass and Qingdao beer were 4.37 and 3.63, respectively. It means both Kvass and Qingdao beer are acidic, but not neutral beverages. The pH value of Kvass in both systems were nearly identical during the whole testing time. The pH value of Kvass in both systems increased in the first 71 hours to around 4.624.81, and then gradually decreased over time to reach 2.57 and 2.54. The pH value of Qingdao beer in the opened and closed systems increased over time in the first 71 and 144 hours to 3.86 and 4.57, and then gradually decreased to reach 4.09 and 3.85.

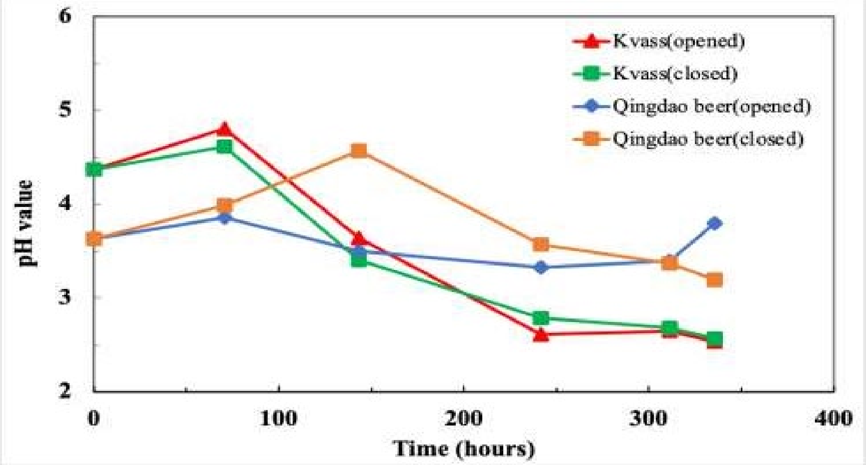


Figure 7. The variation of pH value during the testing time for Kvass and Qingdao beer in the opened and closed systems

Figure 8 is the general corrosion rate of Kvass and Qingdao beer in the opened and closed systems. The corrosion rates in Qingdao beer for both systems were lower than that in Kvass. The corrosion rate in Qingdao beer for the opened system was higher than that in the closed system, which showed a similar trend as Coca Cola and Laoshan Cola. It is interesting that a higher corrosion rate in Kvass was recorded in the closed system.

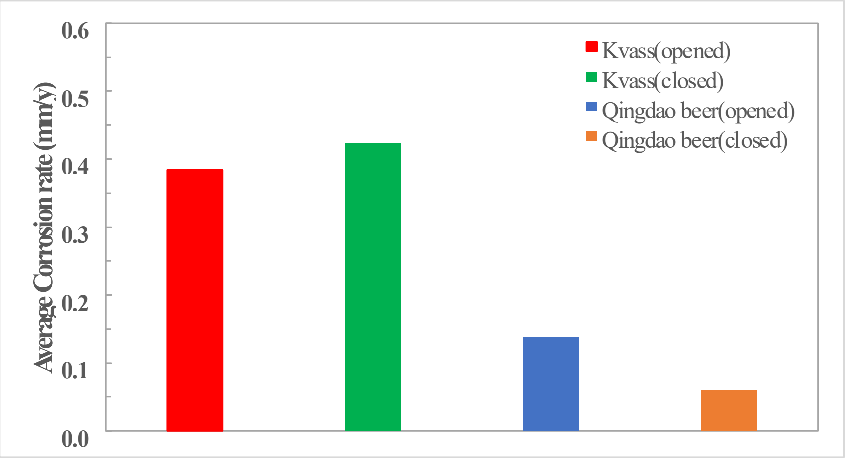
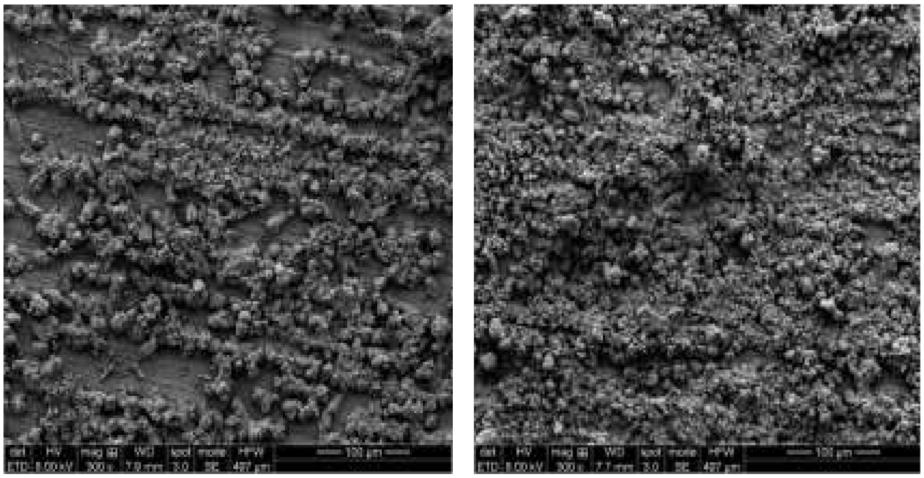


Figure 8. Average corrosion rates of X-60 mild steel exposed to Kvass and Qingdao beer in both opened and closed systems

Figure 9 presents SEM morphologies of X-60 mild steel exposed to Kvass and Qingdao beer in the opened and closed systems for 336 hours with the corrosion product. The metal surface was partially covered by corrosion product in each case, which provided a pathway for corrosive species to reach metal surface. More corrosion product was accumulated in Kvass for closed system while more corrosion product was observed in Qingdao beer in the opened system.



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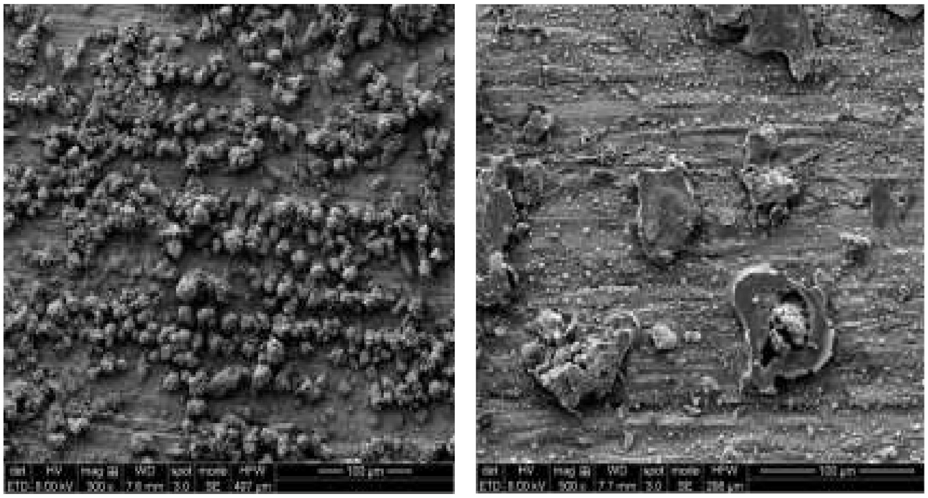
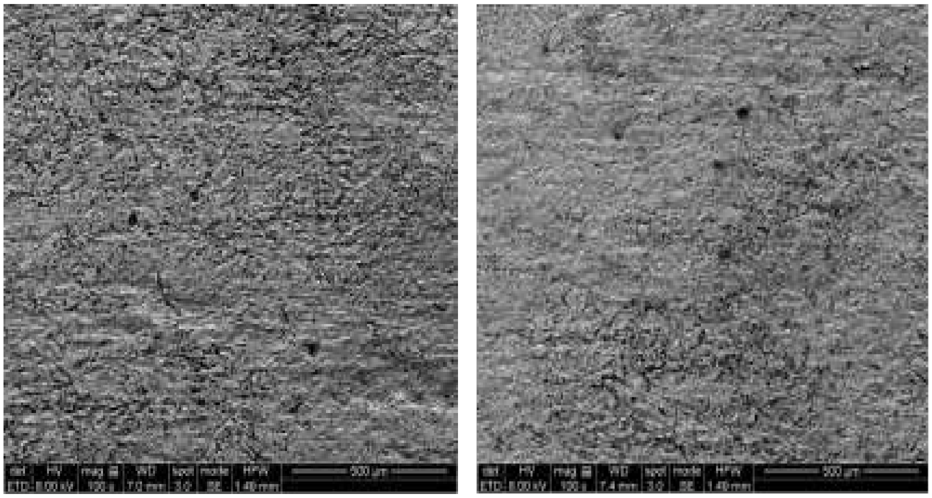


(c) (d)

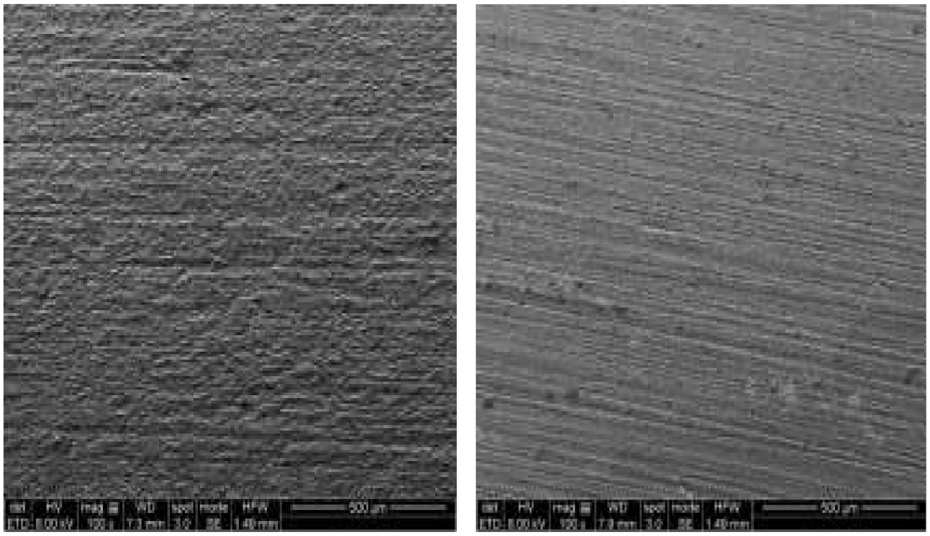
Figure 9. SEM images of the X-60 corroded surface with corrosion product ((a) Kvass in the opened system, (b) Kvass in the closed system, (c) Qingdao beer in the opened system, (d) Qingdao beer in the closed system)

Figure 10 shows SEM morphologies of X-60 mild steel exposed to Kvass and Qingdao beer in the opened and closed systems for 336 hours without the corrosion product. Serious corrosion attack was present on each coupon except for Qingdao beer in closed system. The polishing marks prior to the experiments were still visible on the coupon surface for Qingdao beer in closed system, which was in good agreement with the relatively low corrosion rate in Figure 8.

X-60 mild steel experienced both general corrosion and pitting corrosion in Kvass. Only general corrosion was observed on the sample surface in Qingdao beer. The general corrosion rate for Kvass in closed system was higher than that in opened system while it was opposite for Qingdao beer.



(a) (b)



(c) (d)

Figure 10. SEM images of the X-60 corroded surface without corrosion ((a) Kvass in the opened system, (b) Kvass in the closed system, (c) Qingdao beer in the opened system, (d) Qingdao beer in the closed system)

Corrosion Behavior in the Laoshan Soda and Laoshan Oldenlandianwater

Figure 11 presents the change of pH value with time for Laoshan Soda and Laoshan Oldenlandianwater in the opened and closed systems. The initial pH was around 6 at each test, which means that both Laoshan soda and Laoshan oldenlandianwater were not alkaline. The pH values at each test generally increased with time.

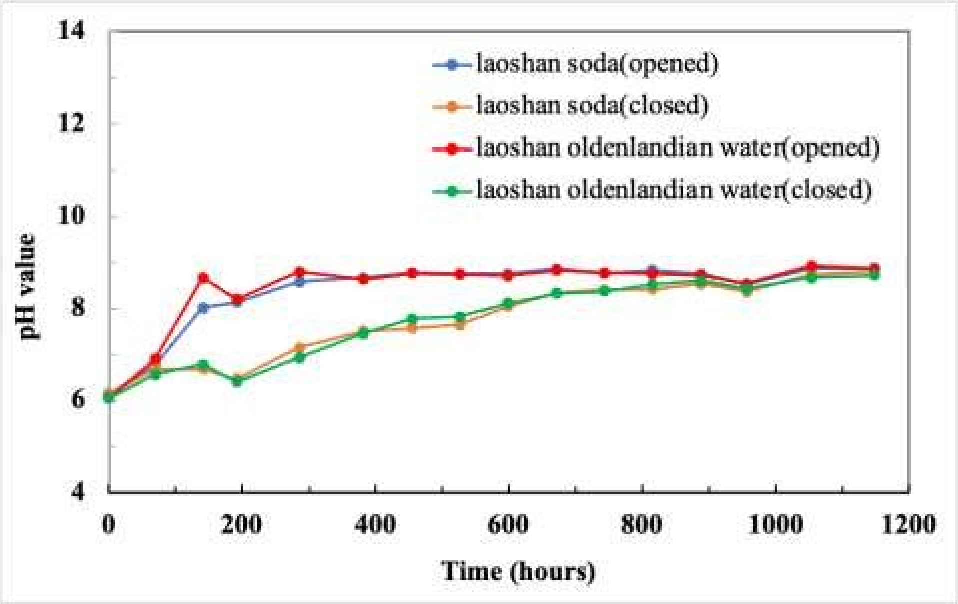


Figure 11. The variation of pH value during the testing time for Laoshan Soda and Laoshan Oldenlandianwater in the opened and closed systems

Figure 12 shows the general corrosion rate of Laoshan Soda and Laoshan Oldenlandianwater in the opened and closed systems. The average corrosion rate of both Laoshan soda and Laoshan oldenlandianwater were higher in the opened system than that in the closed system. The average corrosion rate of Laoshan soda and Laoshan oldenlandianwater were similar in the closed system. The average corrosion rate of Laoshan oldenlandianwater was slightly higher than that of Laoshan soda in the opened system.

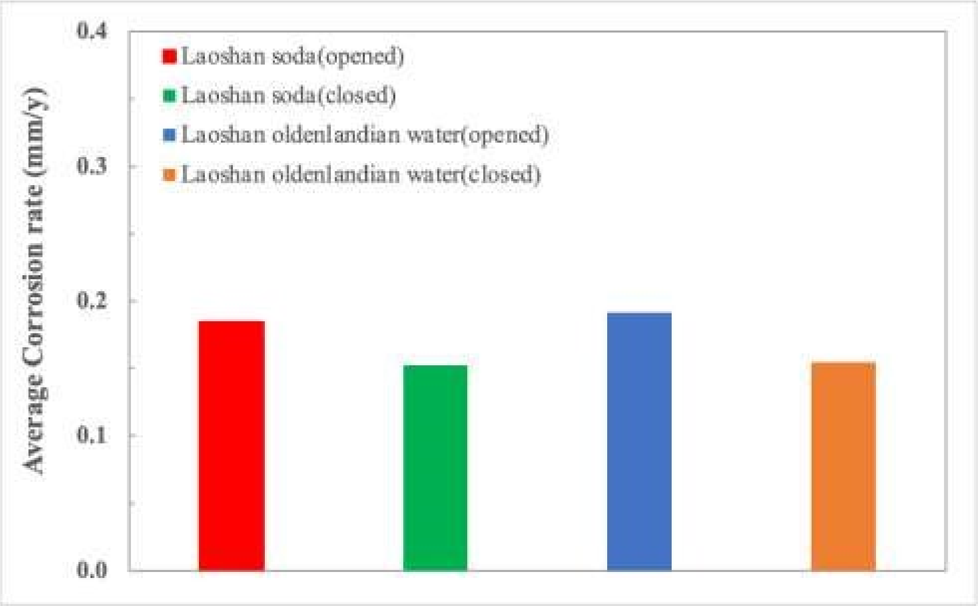
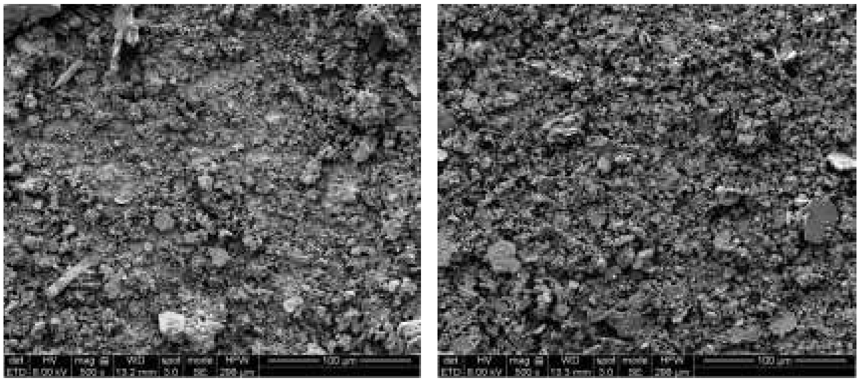


Figure 12. Average corrosion rates of X-60 mild steel exposed to Laoshan Soda and Laoshan Oldenlandianwater in both opened and closed system

Figure 13 shows SEM morphologies of X-60 mild steel exposed to Laoshan Soda and Laoshan Oldenlandianwater in the opened and closed systems for 1148 hours with the corrosion product. Thick and porous flaky corrosion product accumulated on all metal surfaces. Larger pieces of corrosion product particles were observed in Laoshan Oldenlandianwater than that in Laoshan soda.



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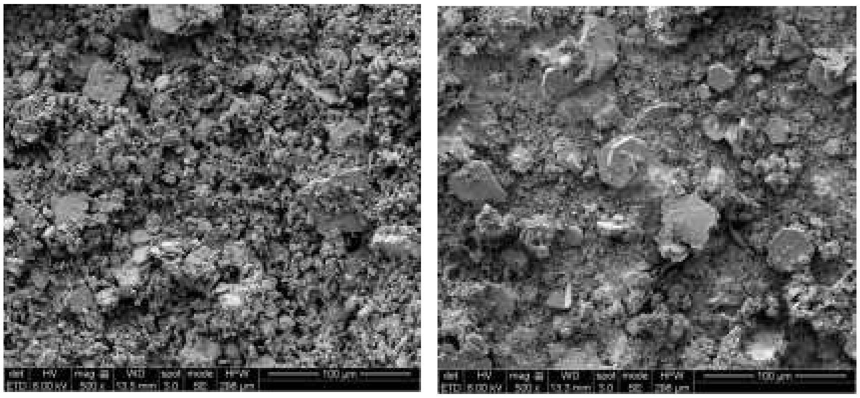
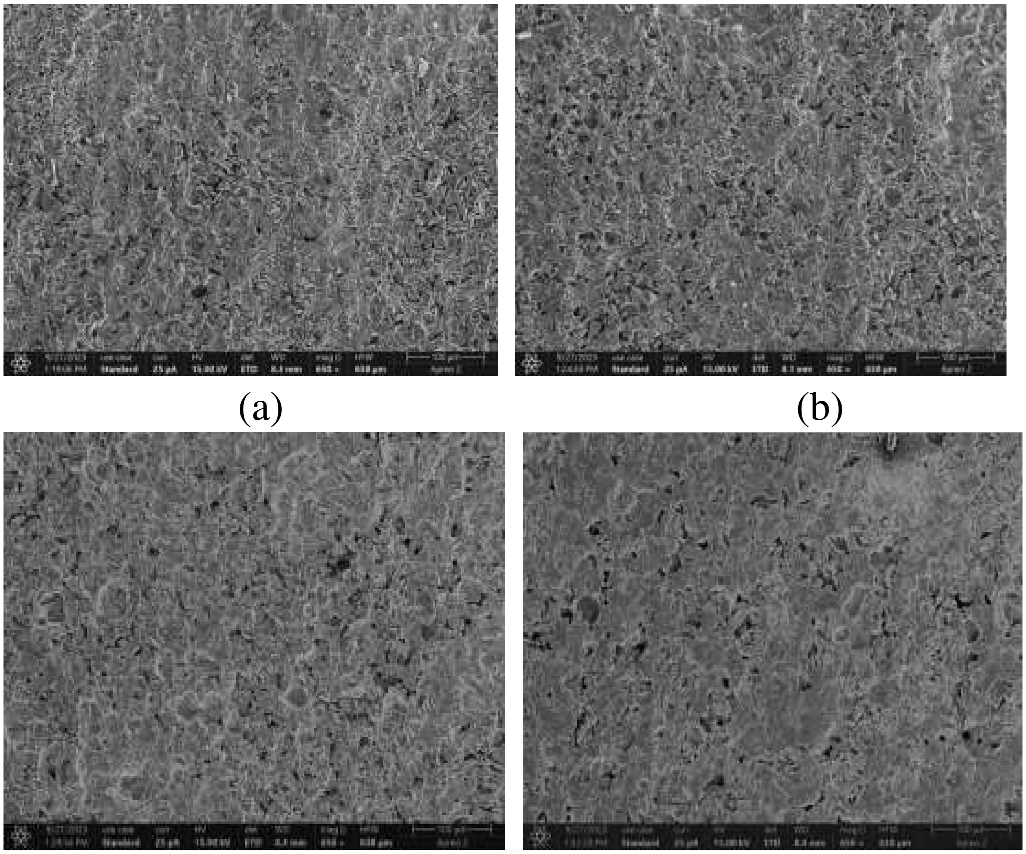


(c) (d)

Figure 13. SEM images of the X-60 corroded surface with corrosion product ((a) Laoshan Soda in the opened system, (b) Laoshan Soda in the closed system, (c) Laoshan Oldenlandianwater in the opened system, (d) Laoshan Oldenlandianwater in the closed system)

Figure 14 shows SEM morphologies of X-60 mild steel exposed to Laoshan Soda and Laoshan Oldenlandianwater in the opened and closed systems for 1148 hours without the corrosion product. Serious general corrosion as well as pitting corrosion was observed at each case.

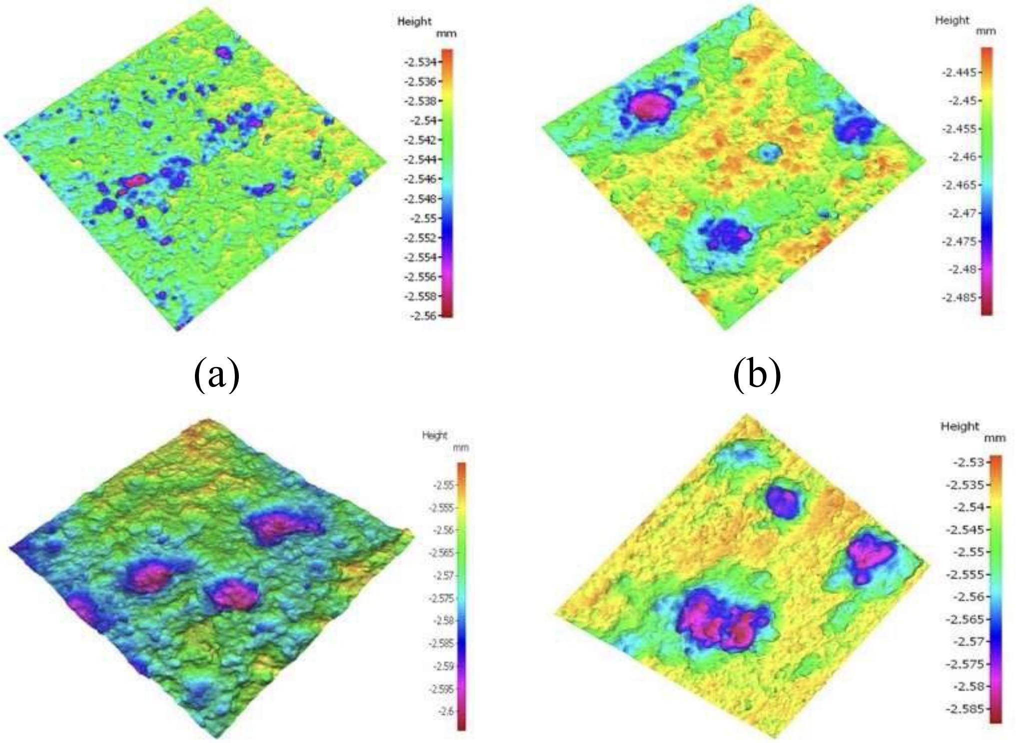


(a) (b)

(c) (d)

Figure 14. SEM images of the X-60 corroded surface without corrosion ((a) Laoshan Soda in the opened system, (b) Laoshan Soda in the closed system, (c) Laoshan Oldenlandianwater in the opened system, (d) Laoshan Oldenlandianwater in the closed system)

Pits were observed in each test by IFM as shown in Figure 15 after corrosion product was removed. The depth of pits was measured by IFM, and then the maximum pitting corrosion rate was obtained.



(a) (b)

(c) (d)

Figure 15. 3D profilometry images of X-60 steel surfaces after removal of corrosion products ((a) Laoshan Soda in the opened system, (b) Laoshan Soda in the closed system, (c) Laoshan Oldenlandianwater in the opened system, (d) Laoshan Oldenlandianwater in the closed system)

Figure 16 presents the pitting corrosion rate of Laoshan Soda and Laoshan Oldenlandianwater in the opened and closed systems. The pitting corrosion rates of Laoshan oldenlandianwater in both systems were much higher than that in Laoshan soda. The pitting corrosion rate of Laoshan oldenlandianwater was higher in the opened system than that in the closed system. However, the pitting corrosion rate of Laoshan soda was lower in the opened system than that in the closed system.

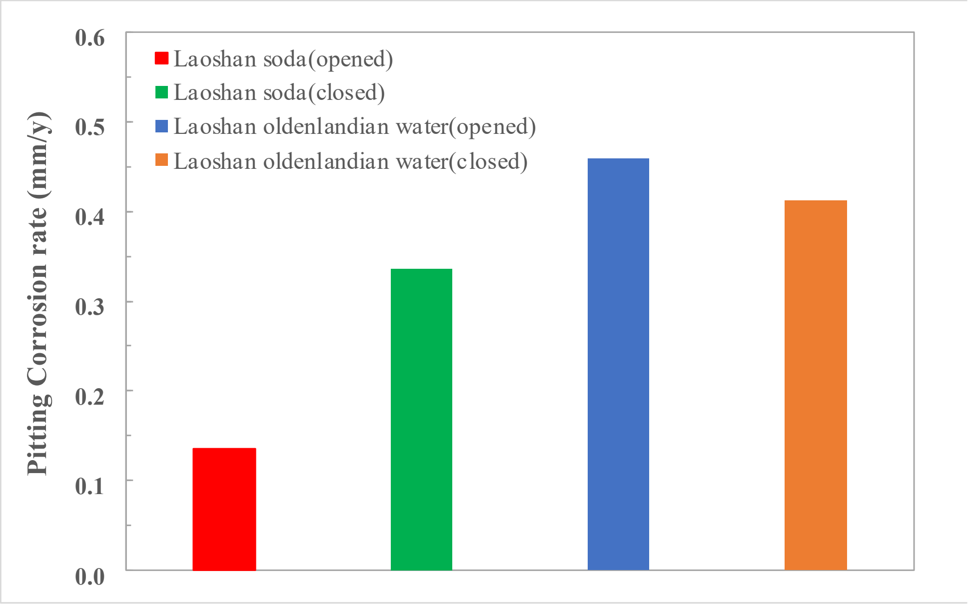


Figure 16. Pitting corrosion rates of X-60 mild steel exposed to Laoshan Soda and Laoshan Oldenlandianwater in both opened and closed systems

Comparison of the Corrosion Behavior of all the Tested Beverages and Tap Water

Comparison of Initial pH

Table 1 indicates the initial pH value of different beverages and tap water used in the present study. It shows that Coca Cola and Laoshan Cola had pH values of 3.58 and 3.74. Kvass and Qingdao beer had pH values of 3.63 and 4.37. Laoshan Oldenlandianwater and Laoshan soda had pH values of 6.06 and 6.15. Tap water had a pH value of 7.47.

Table 1. Initial pH of different beverages and tap water

Substances	pH
Coca Cola	3.58
Laoshan Cola	3.74
Kvass	3.63
Qingdao beer	4.37
Laoshan Oldenlandianwater	6.06
Laoshan soda	6.15
Tap water	7.74

Comparison of Corrosion Rate in Opened and Closed Systems

Figure 17 presents the corrosion rates in different beverages and tap water for the opened system. The lowest and highest corrosion rates were measured in Qingdao beer and Kvass for all the beverages. The tap water had a higher pH value (7.74) than all the other beverages, but the corrosion rate was close to Qingdao beer, which had a pH value of 4.37. Compared to Laoshan Cola, Coca Cola had a lower pH value and a higher general corrosion rate. The pH value of Kvass was lower than Qingdao beer, but a higher general corrosion rate was recorded in Kvass. Even though Coca Cola and Kvass had similar pH values, the general corrosion rate in Kvass was much higher than that in Coca Cola. The pH value in Laoshan Soda was slightly higher than that in Laoshan Oldenlandianwater, but the general corrosion rate in Laoshan Oldenlandianwater was slightly higher than that in Laoshan Soda. Therefore, the corrosion rate of beverage in the opened system was independent of pH value.

There are a lot of different chemical components in each beverage which may affect the corrosivity of the beverage. The interactions of the various compounds contained in drinks are complex and probably synergetic. CO_2 was gradually released from the beverages in the opened system and oxygen was dissolved in the beverage. Oxygen and the component of each beverage influenced the corrosion rate in the opened system. The concentration of each chemical component in the beverage was unknown. As a result, it is difficult to identify which one was the main cause of the corrosion.

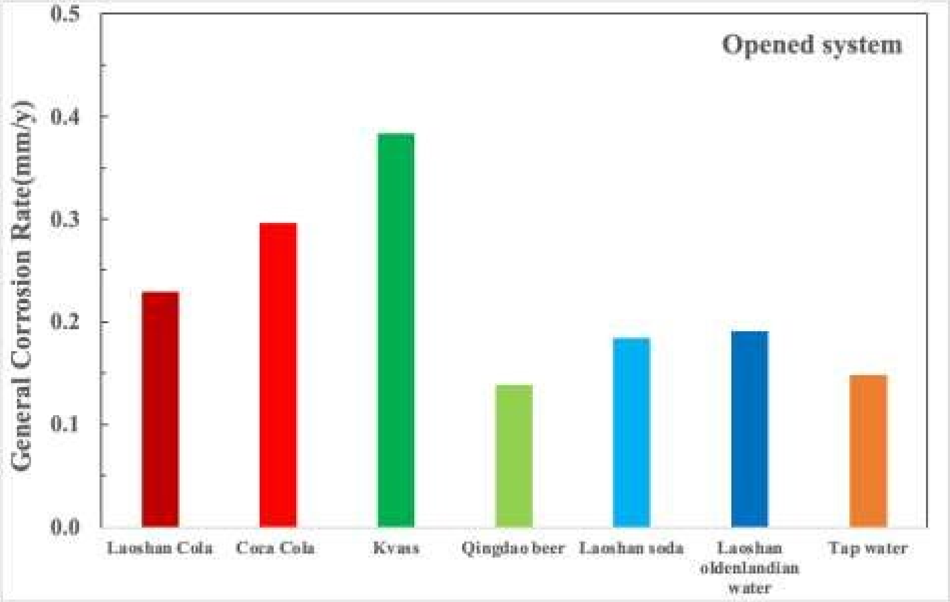


Figure 17. Comparison for the corrosion rate of different beverages and tap water in the opened system

Figure 18 shows the comparison for the corrosion rate of different beverages in the closed system. Tap water was added to this graph for comparison with other beverages though it was tested in the opened system. The corrosion rate in each beverage had the similar changing trend as that in the opened system. The only difference was the corrosion rate in tap water was close to Laoshan Cola, Laoshan soda, and Laoshan Oldenlandianwater. Therefore, the corrosion rate of beverage in the closed system was also independent of pH value.

Compared to the opened system, each beverage had a lower corrosion rate in the closed system except for Kvass. It suggests the CO_2 in the beverages was one of the most important factors to affect the corrosivity of beverages.

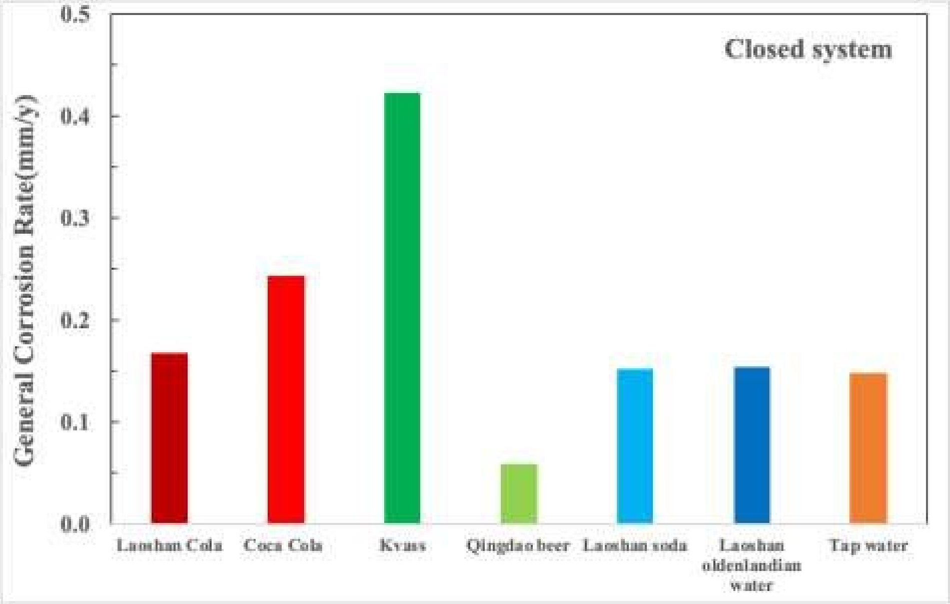


Figure 18. Comparison for the corrosion rate of different beverages and tap water in the closed system

The ranking of aggressiveness of the beverages and tap water studied from high to low was given by the corrosion rate based on the weight loss measurements, and it was as follows: Kvass, Coca Cola, Laoshan Cola, Laoshan Oldenlandianwater, Laoshan soda, tap water, and Qingdao beer.

Future Research

For future research, electrochemical measurement could be applied to provide a more precise description of the variation in the corrosion rate with time. The composition of corrosion product could be analyzed to explain the corrosion mechanism.

Conclusions

- Based on the measured pH values, both Laoshan soda and Laoshan oldenlandianwater were not alkalinous beverages, Kvass, Qingdao beer, and tap water were not neutral drinks, in contrast to common believes.
- The corrosivity of each beverage in both opened and closed systems were independent of pH value.
- CO_2 released from beverages affected their corrosion ability. The ranking of aggressiveness of the beverages and tap water studied from high to low was: Kvass, Coca Cola, Laoshan Cola, Laoshan Oldenlandianwater, Laoshan soda, tap water, and Qingdao beer.
- Pitting corrosion occurred in all tested beverages, except for Qingdao beer which only experienced general corrosion in both systems.

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