Int. J. Electrochem. Sci., 13 **(2018)** 1603 – 1613, doi: 10.20964/2018.02.32

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Short Communication

Effect of soil moisture content on corrosion behavior of X70 steel

Fei Qin[1], *Changliang Jiang*[2], *Xinhua Cui*[2], *Qiang Wang*[2], *Juhong Wang*[2] *Rui Huang*[2], *Datao Yu*[2], *Qing Qu*[3], *Yingjie Zhang*[1,4], *Peng Dong Peng*[1,4,*]

[1] National and Local Joint Engineering Laboratory for Lithium-ion Batteries and Materials Preparation Technology, Key Laboratory of Advanced Battery Materials of Yunnan Province, Faculty of Materials Science and Engineering, Kunming University of Science and Technology, Kunming 650093, China.
[2] CNPC South-east Asia Pipeline Co.,Ltd, Beijing 100000,China
[3] Faculty of chemical science and Engineering, Yunnan university, Kunming 650091,China
[4] Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Kunming 650093, China.
[*]E-mail: dongpeng2001@126.com

Received: 23 September 2017 / *Accepted:* 23 November 2017 / *Published:* 28 December 2017

The effects of moisture content on corrosion of X70 steel in soils from different regions containing Muse, Tungtha, Made Kyun and Made Kyun beach in Myanmar were studied by polarization curves, electrochemical impedance spectroscopy and SEM. It was found that the corrosion rate law of X70 steel in each studied soil tends to be different with the change of moisture content due to the combined effects between soil moisture content and chloride ion content. The values of the corrosion rate were maxima with soil moisture content of 20% except that for the Muse soil where the corrosion rate was minimal with moisture content of 20%. The values of E_{corr} were shifted to more negative values with increasing soil moisture content of up to 60%, and then there was an appreciable increase in the value of E_{corr}. However, the value of E_{corr} was shifted to more negative value with increasing Made Kyun soil moisture content of up to 80%. A good uniformity between the data obtained from polarization curves and EIS measurements results. X70 steel was serious corroded in Made Kyun beach and Made Kyun regions via the data of EIS, polarization curves and SEM result from the different content of chloride in different areas.

Keywords: X70 steel; soil corrosion; moisture content; EIS; polarization curve

1. INTRODUCTION

Sino-Myanmar oil and gas pipeline is China's fourth largest energy import channel following the Sino-Asian oil and gas pipeline, Sino-Russian crude oil pipeline, sea channel. It includes the parallel laying of crude oil pipelines and natural gas pipelines, which can transport crude oil directly from the southwest to the mainland without the Malacca Strait. Sino-Myanmar oil and gas pipeline will transport crude oil to domestic from Muse in Myanmar. Sino-Myanmar oil and gas pipeline has important strategic significance for the protection of China's energy supply, economic sustainable development and so on many aspects. Therefore, the safe operation of oil and gas pipeline is one of the major issues of primary concern. The X70 steel is adopted in the whole process of China Myanmar oil and gas pipeline project, which promotes the development and utilization of X70 steel in China. Most of the oil and gas pipelines were buried in the ground, the span length of pipeline in Myanmar is 771 kilometers long, passing through different regions. Soil corrosion problems can also be different due to the difference of soil salt content, oxygen content, temperature and microbial species in various of soils [1, 2]. Soil corrosion is an important factor that threatens the safe operation of pipeline, and is also the basic cause of pipeline corrosion failure [3, 4]. It is very important for efficiency and safety of X70 pipeline steel to study the impact of soil nature on corrosion of X70 steel [5]. Water content is an important factor in soil corrosion, on the one hand, the water makes the soil become an electrolyte that it forms a prerequisite of the corrosion of the battery ; on the other hand, water content significantly affects the physical and chemical properties of soil[6, 7]. The effect of soil moisture on the corrosion of X70 pipeline steels was investigated by several authors in recent years [8-13]. In addition, chlorine ion is a significant role to influence the pitting of X70 steels in nature soil [14, 15]. The Muse region is the connecting point of the Myanmar section and the Chinese section of the Sino-Myanmar oil and gas pipeline project near the Shweli River, the soil corrosion factor is complex; Made Kyun beach area and Made Kyun belong to Kyaukpyu, which is the starting point for the Sino-Myanmar oil and gas pipeline near India Ocean, the content of chloride ion in the four places is quite different; Taungtha area is part of Mandalay, which is middle section of Myanmar section. Therefore, these four places are typical Myanmar soil environment.

In order to discuss the possible cause of the corrosion of the pipeline, it is necessary to consider the corrosion resistance of X70 steel in these four areas. Field burying experiment is the most reliable method to study soil corrosion, but it is time-consuming and not be used for short-term soil corrosion research[16-17].The present research is attempt to reveal the effect of soil moisture content on the corrosion behavior of X70 steel in soils from different regions containing Muse, Taungtha, Made Kyun and Made Kyun beach in Myanmar at ambient（25ºC±1ºC） using SEM and electrochemical methods such as polarization curves and EIS, accumulating data of environmental corrosion of X70 steel and discussing the corrosion law, providing the basis for the application and protection of buried for X70 steel in the soil.

2. EXPERIMENTAL PART

2.1. Test soils

The test soils were obtained from different areas (Muse, Taungtha, Made Kyun and Made Kyun beach) in Myanmar. Fig.1 shows the geographic locations of these cities. All the soil samples were collected at 1m depth, which were put in a fabric bag and taken to the laboratory. The soil samples were grinded by natural drying and passed through 20 mesh screen. The soil solution was a mixture of soil and de-ionized water with moisture contents of 20%, 40%, 60% and 80%, respectively, after that the soil solution is sealed and put into the incubator with 25ºC. ORP, pH and chloride ion of the soil solution were measured just before the experiments. The measured values are given in the Table1. It can be found that there is major difference between the chloride ion concentration and pH of the studied soils, but the ORP is almost no difference.

Table 1. The Chloride ion concentration and pH of test soils

Test soil	pH	Cl- /%	ORP /mV
Taungtha	6.68	0.008	246
Muse	8.43	0.043	232
Made Kyun beach	5.82	0.246	252
Made Kyun	4.91	0.036	263

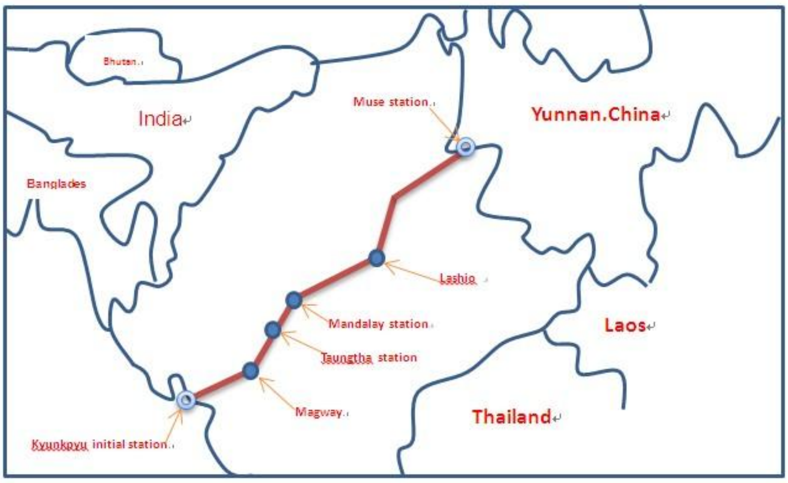


Figure 1. Locations of soil samples collecting in Myanmar

2.2. Materials

The experimental material is an X70 pipeline steel which is produced by Shanghai Baoshan Iron and Steel, the chemical components are shown in Table1. Specimens were cut from a plate along the longitudinal direction with the gauge size of 25 x 10 x 2mm. The working surface area was 2.5cm^2, and the other area was masked using epoxy resin. Before the experiment, the gauge part the specimens were mechanically wet-milling to 1000–grit using silicon carbide papers and cleaned with ethanol and distilled water and finally dried in the desiccator. A newly polished specimen was used for each test.

Table 2. Chemical composition of X70 steel used in the experiment (unit: mass fraction%)

Experimental material	C	Si	Mn	P	S	Fe
X70 steel	0.061	0.24	1.53	0.011	0.0009	balance

2.3. Electrochemical measurements

The processed X70 steel sample was embedded in a 250ml beaker with filled the soil sample, which was connected with a wire and placed in a constant temperature and humidity machine. The electrochemical test was performed by the Metrohm company's electrochemical workstation connecting with a personal computer used the three electrode system. A rectangular specimen of X70 steel was used as working electrode. A platinum sheet was used as the auxiliary electrode and saturated calomel electrode was used as reference electrode. Before all electrochemical measurements, each specimen was applied for 2 min as an initial conditioning treatment followed by exposure at OCP until reaching a stable potential.

Electrochemical impedance spectroscopy measurements were carried out using the same three electrode system as mentioned above. During Electrochemical impedance spectroscopy, an AC disturbance signal of 1 mV was applied on the electrode at the OCP. The measured frequency ranged from 0.01 to10^5Hz. All the electrochemical measurements were done twice at (25ºC±1ºC). EIS results were fitting to equivalent circuit using computer program naming ZsimpWin. The Potentiodynamic polarization curve measurement was collected at potentiodynamic scan rate of 5mV/s between -1.5V and +0.5V relative to E_{oc}. PDP results were fitting to equivalent circuit using computer program naming Zview. X70 steel samples were removed after electrochemical testing, and cotton swab was used to wipe the soil adhered to the surface of the sample. The morphology of X70 steel surface after finishing potentiodynamic polarization was detected by scanning electron microscopy.

3. RESULTS AND DISCUSSION

3.1. Microscopic morphology

Fig.2 shows microscopic photographs of the X70 steel specimens in studied soils buried for 7 days with moisture content of 40%. All photographs show the surface features of the studied specimens after treatment with the cleaning solution. It was found that cracks appeared in corrosion products of the surface of X70 steel buried for 7 days in Made Kyun beach and Made Kyun soils. It was shown that the surface corrosion products had no protective effect on the matrix, and then corrosive ions could penetrate the surface of the substrate through cracks and continued to react with metal. However, in the other two places, there were a little of corrosion products on the surface of the X70 steel. In addition, the surface of the electrode had lost the original metal luster. The strip groove on the surface of X70 steels were caused by scratch. The corrosion content of X70 steels in Made

Kyun beach and Made Kyun areas were more serious than that in Muse and Taungtha due to the higher chloride ion content in the previous two places. Chloride ions could increase soil conductivity, resulting in rapid accumulation of corrosion products on the surface of specimens [18-19]. From Fig-(b) and Fig-(d), it can be seen that there are cracks in the corrosion products, and chloride ions will reach the surface of carbon steel through these cracks and will adsorb on passivation film. Due to the small radius and high activity of chloride ions, chloride ions penetrates passivation film structure defects department, resulting in the destruction of the passive film [20-21]. Due to the intrusion of chloride ion, the surrounding environment of carbon steel is inhomogeneous to form a salt concentration battery, and the chloride ions depolarize and the corrosion of carbon steel aggravates [22]. In addition, chloride ions are repeatedly recycled as chloride ions are not consumed during the corrosion of carbon steel itself. So carbon steel continues to be corroded.

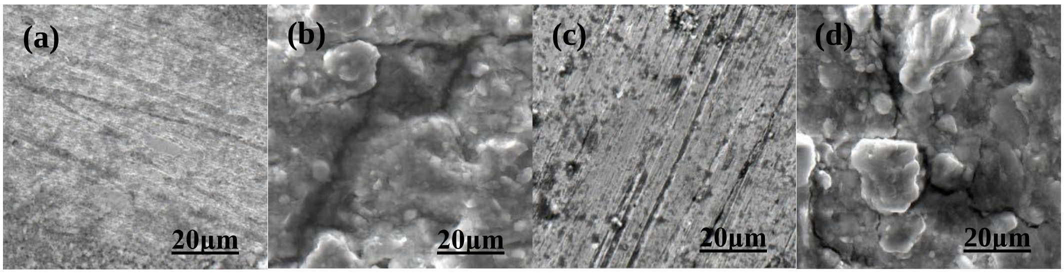


Figure 2. Microscopic photographs for X70 steel in a Muse,b Made Kyun beach and c Taungtha and d Made Kyun soils with moisture content of 40%

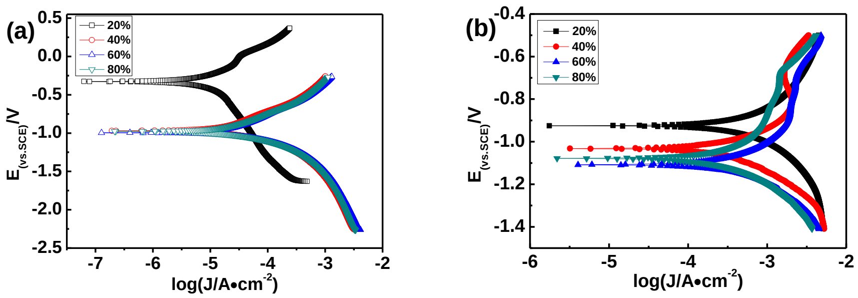
3.2. Polarization curves

The potentiodynamic polarization curves of cathodic and anodic for X70 steels in the studied soils with different moisture contents and at(25ºC±1ºC) are shown in Fig.3. Generally speaking, the curves show a Tafel behavior for low polarization. It is observed that a potential range in limited change of the current density.

It is proverbial that Tafel relationship is applicable for pure activation control, or charge transfer control. In addition, the concept of concentration polarization is taken into account. The reaction rate is fast enough that the electrochemical reaction involves oxidation and reduction at steel substrate surface.

Fig.3 shows that at the potential of about -800mV for X70 steel in each soil, the anodic curves are shifted to higher current densities with increasing moisture content up to 60%. There is then no appreciable change in the current density observed as the Muse soil moisture increased over 40% or the Taungtha soil moisture increased over 20%. In addition, at the potential of from -940mV to -640mV for X70 steel in Made Kyun beach and Made Kyun soil, there is little change in the current density observed as potential change, and then the current density is increased greatly beyond this the potential region due to the presence of chlorine ions in the soil. The adsorption of chlorine ions on the surface of the electrode resulted in the destruction of the passive film and corrosion rate is greatly increased. In addition, at potential of about -1300mV for X70 steel in Made Kyun beach soil and Made Kyun soil, the cathodic curves are shifted to higher current density with soil moisture content of 20%, after that the current density appreciable is decreased as moisture content increased over 20%; at the potential of about -1500mV for X70 steel in Muse soil or Taungtha soil, it is shifted to higher current density with increasing soil moisture content of up to 60% and 40% respectively. The above polarization curves show that the effect of soil species and moisture content on the corrosion rate is not straightforward. It is necessary to estimate i_{corr} values for the corrosion of X70 steel in studied soils at different moisture contents. Polarization curve parameters for the corrosion of X70 steel in studied soils at different moisture contents are recorded in Table3. The results are obtained as can be seen from the Table3, the values of icorr tend to decrease with the increase of Made Kyun soil moisture content; the values of i_{corr} tend to increase as Muse soil moisture content increases, up to a maximum value at 60%, then tend to decrease at a moisture content of more than 60%; the values of i_{corr} tend to be smaller with Taungtha soil moisture content up to 40%, after that the values of i_{corr} is imperceptible increased as moisture content increased over 40%; The values of i_{corr} tend to decrease with the increase of Made Kyun soil moisture content. In fact, several researchers have demonstrated that the corrosion behavior of pipeline steel is disparate with the variation of different soil moisture [23-24].The studied results that the corrosion law with the change of water content would be different has been observed.

The corrosion law of X70 steel in different soils is different resulted from the combined effects of dissolved oxygen and chloride ion in soil. The cathode process of electrochemical reactions was controlled by dissolved oxygen and chloride ions combined with dissolved metal cations to promote electrochemical reactions. However, the chloride concentration shows a rather pronounced variation with dissolved oxygen concentration [25-27]. Chloride ions not only controlled the cathode process but also the anode process. Due to the increase of chloride ion concentration, the conductivity of soil solution increases and the action of chloride ion strengthens, and the corrosion of carbon steel rapidly increases. The increase of conductivity of the soil solution makes chloride and iron ions to be transported faster, and the rapid combination of chloride and iron ions results in faster anodic processes and increase of the corrosion of the carbon steel. When the chloride ion concentration exceeds a certain value, the soil solution oxygen solubility decreases and the diffusion rate decreases. In most cases, the oxygen-absorbing corrosion process is governed by the oxygen diffusion process. During diffusion-controlled corrosion, the rate of corrosion depends on the oxygen diffusion rate. Oxygen diffusion rate decreases, the corrosion rate will be reduced. Therefore, chloride ions also control the cathode process



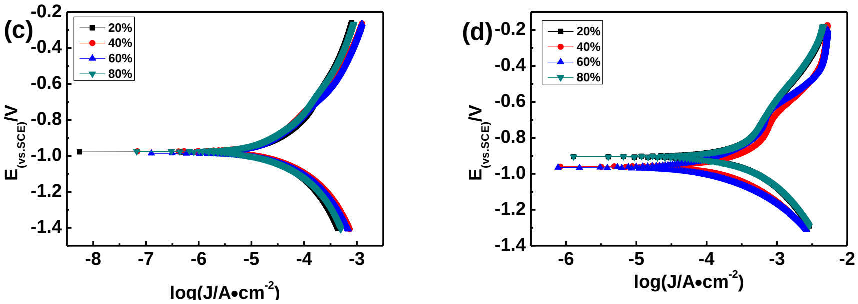


Figure 3. Polarization curves for X70 steel in a Muse,b Made Kyun beach and c Taungtha and d Made kyun soils of different moisture contents

Table 3. Potentiodynamic polarization parameters of X70 steel in Muse, Made Kyun beach, Taungtha ,and Made Kyun soils with different moisture content levels

PDP parameters	Moisture content (wt%)			
	20	40	60	80
Muse				
$-E_{corr}$ (mV)	326.55	969.66	995.22	976.02
i_{corr} (μA/cm2)	**1.98**	**5.38**	**28.22**	**17.08**
Made Kyun beach				
$-E_{corr}$ (mV)	925	1032.5	1108.3	1078.5
i_{corr}(μA/cm2)	**1695**	**459.53**	**1264.1**	**1051.9**
Taungtha				
$-E_{corr}$ (mV)	977.92	975.34	985.41	975.76
i_{corr}(μA/cm2)	**39.28**	**20.98**	**21.22**	**25.95**
Made Kyun				
$-E_{corr}$ (mV)	905.11	960.46	965.32	974.27
i_{corr}(μA/cm2)	**799.72**	**218.6**	**128.52**	**97.96**

3.3. Electrochemical Impedance Spectroscopy(EIS)

Electrochemical impedance spectroscopy for X70 steel in studied soils with different moisture contents and at ambient (25±1°C) are shown in Fig.5. There are high frequency (left-hand loop of the Nyquist plot) and low frequency (right loop of the Nyquist plot) in Nyquist plot. High frequency part reflects the information of rust layer, corresponds to compactness and thickness of rust layer; low frequency part corresponds to the charge transfer process at the metal/film and metal/soil interfaces, involves the oxidation of iron and the reduction of oxygen. As can be seen from the graph， it is illustrated that X70 steel starts to be corroded for two capacitive semicircles presented in studied soils and the semicircles at high frequency are much smaller than the semicircles at low frequency. Moreover, the deviation from the ideal semicircle with dispersion effect appears in impedance spectrum due to X70 steel / soil is a complex interface and inhomogeneous the surface of steel[22].

Fig.4-(a) shows that EIS for X70 steel in Muse soil buried for 7 days with different moisture contents. The capacitive radius is decreased first and then increased with the increase of soil moisture content. The capacitive radius is shifted to smaller with increasing moisture content of up to 60%, after

that the capacitive radius is imperceptible increased. Fig.4-(b) shows that EIS for X70 steel in Made Kyun beach soil buried for 7 days with different moisture contents. The capacitive radius is shifted to bigger with increasing moisture content of up to 80% except for that moisture content is 40% which the radius is maximal. Closing to 45 degrees straight appeared in the low frequency, putting up a Warburg impedance characteristic of spreading characteristics as soil moisture content increased over 40%. Fig.4-(c) shows that EIS for X70 steel in Taungtha soil buried for 7 days with different moisture contents. The capacitive radius is shifted to smaller with increasing moisture content of up to 80% except for that moisture content is 20% which the radius is minimal. In addition, it appears a Warburg impedance characteristic of spreading characteristics in the low frequency with increasing moisture content of up to 20%. Fig.4-(d) shows that EIS for X70 steel in Made Kyun soil buried for 7 days with different moisture contents. The capacitive radius is increased with the increase of soil moisture content. EIS for X70 steel performs a double capacitive arc, and it appears a small arc at the high frequency or large radius single capacitive arc at the low frequency. In particular, it appears a real part of inductive arc contraction with moisture content of 20%. In addition, when the soils except for Made kyun soils moisture content is up to 40%, the impedance spectrum shows the characteristics of diffusion impedance, which indicates that the electrochemical reaction is dominated by diffusion. In fact, several researchers have demonstrated that concentration polarization can be neglected with the increase of moisture content[3, 28-29]; still some researchers think that the permeability of soil decreases, leading to the diffusion of oxygen into the control step of electrochemical corrosion process due to the increase of water content[9,11].

To determine the resistance of the electrochemical reaction occurred on X70 steel specimen, the measured impedance data were analyzed based upon the electric equivalent circuits which are given in Fig.5, the fitting results of relevant parameters are shown in Table4. The equivalent circuit consists of R_s, solution resistance, Q_m, corrosion product film interface capacitance, R_m, corrosion product film resistance, Q_{dl}, soil/steel interface capacitance, R_{ct}, electrochemical transfer resistance. The value of electrochemical transfer resistance is related to that of corrosion rate. In general, The higher the electrochemical resistance is, the greater the resistance to the electrode reaction and the smaller the corrosion rate of X70 steel will be[30-33], that is consistent with the fitting results of polarization curves. X70 steel is most seriously corroded in Made Kyun beach soil and in Made Kyun soil, followed by Taungtha; X70 steel has the lowest degree of corrosion in Muse soil is investigated by Fig.4 and Table.4. This result is related to the adsorption of anions in the soil on the passive film. Chlorine ions are adsorbed on the local passive film through the pores of the soil which makes the pH value drop rapidly lead to the failure of passive film on the surface of X70 steel due to its high activity and small radius. On the one hand, the electrochemical transfer resistance is much smaller than that of the passive film without chloride ion adsorption on the electrode surface, and the EIS both can differ by several orders of magnitude due to the influence of the potential on chloride ion adsorption; on the other hand, the increase of chloride content leads to an increase in the conductivity of the electrolyte that it leads to a decrease in the electrochemical transfer resistance, which is consistent with the polarization curves.

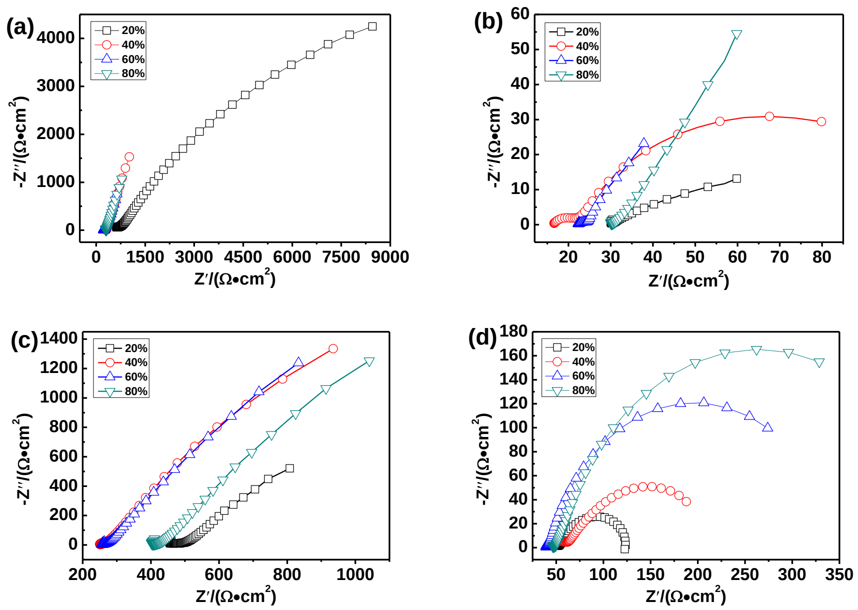


Figure 4. Nyquist plot for X70 steel in a Muse,b Made Kyun beach and c Taungtha and d Made kyun soils of different moisture contents

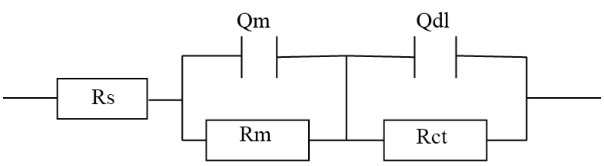


Figure 5. Equivalent circuit of X70 steel in studied soils with different moisture content

Table 4. electrochemical parameters of X70 steel under the influence of different copper content

Moisture content (wt%)		electrochemical parameters						
		R_s ($\Omega\cdot cm^2$)	Y_m ($S^n\cdot\Omega\cdot cm^2$)	n_1	R_m ($\Omega\cdot cm^2$)	Y_{dl} ($S^n\cdot\Omega\cdot cm^2$)	n_2	R_{ct} ($\Omega\cdot cm^2$)
Made Kyun	20	33.82	0.00465	0.149	26.87	0.00254	0.81	**68.48**
	40	38.71	0.00023	0.510	25.38	0.00412	0.68	**168.5**
	60	37.27	0.04894	0.197	21.6	0.00255	0.85	**298.4**
	80	44.72	0.04956	0.445	19.7	0.00256	0.86	**400.3**
Made Kyun beach	20	40.40	0.06835	0.548	49.79	0.05684	0.41	**21**
	40	16.39	0.00099	0.642	6.39	0.01125	0.77	**89**
	60	22.29	0.00302	0.696	1.94	0.04699	0.73	**44.8**
	80	29.88	0.02415	0.719	34.7	0.02398	0.71	**56.6**
Taungtha	20	454	0.00236	0.803	3191	0.00238	0.82	**3045**
	40	247.7	0.00574	0.386	128.7	0.00096	0.87	**6372**
	60	236.6	0.00105	0.821	10800	0.00104	0.80	**6043**
	80	385.8	0.00109	0.822	9408	0.00995	0.83	**5731**
Muse	20	301.4	0.00009	0.534	18780	0.00001	0.26	**7826**
	40	309.2	0.00084	0.735	15540	0.00273	0.56	**7538**
	60	234.8	0.00345	0.481	13290	0.00214	0.81	**5537**
	80	302.4	0.00123	0.728	9655	0.00362	0.48	**6631**

4. CONCLUSIONS

The effect of moisture content on the corrosion behavior of X70 steel in the soils of different regions of Myanmar temperatures(25±1℃)was investigated using SEM, polarization curves, and EIS measurements. Analysis of the obtained data led to the following conclusions.

1. The data obtained from various analysis techniques (Polarization curves and EIS) revealed that the corrosion rate law of X70 steel in each studied soil tends to be different with the change of water content. The values of the corrosion rate are shifted to higher with soil moisture content of 20% except that for the Muse soil where the corrosion rate shifted to lower with moisture content of 20%. The corrosion law of soil samples of X70 steel in these four areas is inconsistent, which is due to the combined action of dissolved oxygen and chloride ions on the electrode surface.
2. The values of E_{corr} are shifted to more negative values with increasing soil moisture content of up to 60%, after which an appreciable decrease in the E_{corr}. In particular, The value of E_{corr} is shifted to more negative values with increasing Made Kyun soil moisture content of up to 80%.
3. Good consistency between the data obtained from polarization curves and EIS measurements. X70 steels are serious corroded in Made Kyun beach and Made Kyun region compared by the data of EIS and polarization curves result from Chloride content difference in different regions.
4. The corrosion products of X70 steel in Made Kyun and Made Kyun beach areas are thicker than that in Taungtha and Muse areas due to the action of chlorine ions. Chloride ions can increase soil conductivity, resulting in rapid accumulation of corrosion products on the surface of specimens.

ACKNOWLEDGEMENTS

This work is supported by the Natural Science Foundation of Yunnan, China (No.2014FA025). National joint engineering laboratory of Kunming University of Science and Technology is gratefully acknowledged for assisting with relevant analyses.

References

1. H. Hoffmeister, *Corrosion*, 61(2005)880.
2. W. Gerwin, R. Baumhauer, *Geoderma*, 96(2000)63.
3. I.S. Cole, D. Marney, *Corros.Sci*, 56(2012)55.
4. M.C. Yan, C. Sun, J. Xu, J. Dong, *Corros.Sci*, 80(2014)309.
5. Al-Hazzaa, M.I, Research Center, College of Engineering, King Saud University, Al-Riyadh (2007).
6. C.F. Dong, X.G. Li, J.W. Wu, *Corros. Sci. Prot. Technol*., 15(2003)154.
7. X. Chen, C.W. Du, X.G. Li, P. Liang, X.R. Lu, *Univ. Sci. Technol. Beijing*, 30(2008)730.
8. X. Nie, X. Li , C. Du, Y. Huang, H. Du, J. Raman. *Spectrosc*, 40(2009)76.
9. M. Zhu, C.W. Du, L. Huang, Z.Y. Liu, T.L. Zhao, Q. Li, X.G. Li, *J. Chin. Soc. Corros. Prot.*, 34(2014)65.
10. G. Su, De. Ding, C.Y. Li, C.W. Du, Z.Y. Liu, X.J. Yang, *Corrosion and Protection*, 37(2016)613.
11. K. Ma, B. Cao, S.M. Chen, *Corrosion and Protection*, 35(2014)922.
12. X.D. Fei, M.Q. Li, H.M. Xu, Y.Q. Li, D.C. Cai, *Corros. Sci. Prot. Technol*, 19(2007)35.
13. E. Noor, A. Al-Moubaraki, *Arab. J. Sci. Eng*, 39(2014)5421.

14. FF. Eliyan, F. Mohammadi, A. Alfantazi, *Corros.Sci*, 64(2012)37.
15. S. Sharifi-Asl, F. Mao, P. Lu, B. kursten, et al. *Corros.Sci*, 98(2015)708.
16. M. Barbalat, L. Lanarde, D. Carnon, et al. *Corros.Sci*, 55(2012)246.
17. Y.J. Tan, *Corros.Sci*, 53(2011)246.
18. H.Z. Abyaneh, A.H. Nazemi, M.R. Neyshabori, K. Mohammadi, G.H. Majzoobi, *Journal of Agricultural and Science*, 1(2005)110.
19. S. Hajrasuliha, D.K. Cassel, Y. Rezainejad, *Geoderma*, 49(1991)117.
20. Y.M. Zeng, J.L. Luo, *Electrochimica Acta*, 48(2003)3551.
21. D.G. Li, Y.R. Feng, Z.Q. Bai, *Acta Chimical Sinica*, 66(2008)1151.
22. Y.H. Wu, S.X. Luo, Y.Y. Fu, et al. *Surface Technology*, 40(2011)65.
23. M.C. Li, H.C. Lin, C.N. Cao, *Corros. Sci. Prot*, *Technol.*, 14(2000)218
24. X.H. Nie, X.G. Li, Q.H. Shen, *J. Master. Eng*, 6(2009)17.
25. A. Whitchurch, *Nature. Geoscience*, 7(2014)82.
26. Y. Li, J. Wu, D. Zhang, Y. Wang, B. Hou, *Journal of Solid. State. Electrochemistry*, 14(2010)1667.
27. K. Jafarzadeh, T. Shahrabi, S.M.M. Hadavi, M.G. Hosseini, *J. Master. Sci. Technol*, 23(2007)623.
28. A.I.M. Ismail, A.M. Ei-shamy, *Applied. Clay. Science*, 42(2009)356.
29. A. Carlos, M. Ferreira, A.C.P. Jose, *Science of the Total Environment*, 388(2007)250.
30. P. Liang, X.G. Li, C.W. Du, X. Chen, L. Zhang, *Corros. Sci. Prot. Technol.*, 21(2009)20.
31. Y. H. Wang, J. Wang, J.B. Zhang, *J. Chin. Soc. Corros. Prot.*, 25(2005)332.
32. J.B. Li, J.E. Zuo, *Corros. Sci. Prot. Technol.*, 21(2009)44.
33. H.P. Yao, M.C. Yan, C. Sun, *J. Chin. Soc. Corros. Prot.*, 34(2014)472.