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Corrosion Rate of Buried Pipeline by Alternating Current

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An alternating current (AC) corrosion on buried pipeline has been studied using coupon and ER probe. Coupons and ER probes were applied to the sites from high value of AC voltage to low value based on the survey of AC voltages on buried gas transmission pipeline over the country. Parameters such as AC current density of coupon, AC voltage, cathodic protection potential, soil resistivity and frequency were monitored continually. Corrosion induced by AC was observed even under cathodically protected condition that met cathodic protection criterion (; below -850 mV vs. CSE). Corrosion rate was affected mainly not by AC voltage but by both of frequency and AC current density. An experimental corrosion rate relation could be obtained according to effective AC current density, in which AC corrosion rate increased linearly with effective AC current density, and its slope was 0.619 in coupon method and 0.885 in ER probes.

Keywords *: AC corrosion, coupon, electric resistance, cathodically protected pipeline, interference*

1. Introduction

Buried pipeline made from steel is apt to be a preferential electrical conductor of stray current because of its superior electrical conductivity. In regard with stray current problem, much effort has been put into DC stray current like subway rail, which led to cumulative experiences and consequent appropriate counter-measures.[1)] However, AC interference has been focused in an aspect of human safety,[2),3)] not in corrosion until late 80s.[4)]

AC induction onto pipeline can be classified into three mechanisms.[5)] Inductive coupling arises where pipeline has common corridor with powerline in length. Where current discharge from electrical grounds into earth entails potential distribution around grounds, resistive coupling arises if pipeline is placed at AC potential distribution. Capacitive coupling may arise during pipeline construction when long pipeline is exposed in the air before burial. This, however, can be neglected after burial. Thus it is both of the inductive and the resistive coupling that affect the buried pipeline in view of AC interference.

It has been generally recognized that AC corrosion at field under cathodic protection condition could be negligible since William's report,[6)] where the amount of corrosion was expressed as percentage of the amount of corrosion that would be caused by an equivalent intensity of direct current (DC). It was shown that AC corrosion rate was less than 1% of that of DC. Regarding with this, Bertocci[7)] demonstrated that relative low current efficiency in AC corrosion was attributed to the fact that majority of ac current flow through electrical double layer capacitor whereas minority of ac current flow through polarization resistance causing charge transfer.

In Germany and Canada at late 80s, however, corrosion cases were reported as consequence of AC corrosion and then, which led to several studies in Germany. Among them, Funk[8)] suggested that accelerated corrosion proceed at above 10 mA/cm^2, and negligible corrosion is anticipated at below 2 mA/cm^2. Peez[9)] obtained maximum penetration in defect size between 0.5 ~ 5 cm^2. These imply that AC corrosion rate cannot be neglected in case AC current density is large in magnitude.

In spite of Kajiyama's[10)] report that AC corrosion rate under the condition of 4 mA/cm^2 in AC current density and -1.3V in off-potential was as small as 1mpy, and Pagano's[11)] report that corrosion rate was decreased with frequency, there has been no report about field test results in an aspect of frequency and there is only a few field reports on AC corrosion rate under cathodic protection potential.

Results of extensive field survey on buried pipelines subjected to AC interference are presented in this study. Emphasis is put on methods to measure and/or monitor the corrosion rate.

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2. Experimental

Coupons were prepared with materials specified in API 5L X65 which were machined to the size of 15(w) x 15(b) x 0.5(t) mm and then grinded by SiC paper (#600). 2 mm diameter hole was perforated in the edge of coupon to connect electrical lead, cleaned ultrasonically in acetone and weighed. As lead was connected, all area including lead except exposing 1 cm^2 was coated by epoxy. Coupons were buried at 1.5 m depths, which was same burial depth of pipeline. Soil at excavation site was applied as backfill. Total numbers of 40 coupons were buried with fairs at each site.

Multi-lined thin ER (MLTER) probe used in this study was fabricated in laboratory scale with originality. Schematic diagram of MLTER probe is shown in Fig. 1. Detailed fabrication condition, process and its reliability test results are described elsewhere.[12),13)] The exposed area of the probe was consisted of 5 lines with 1.0 mm width and uniform 20 mm length. Uniform length was designed to hold even resistance between lines. Total exposed area of 2.7 cm^2 was distributed over 1.7 mm x 20 mm area.

One set composed of A/D converter and logger was installed between coupon and pipeline, the former was fabricated to convert ac current to dc voltage in the range from 1 to 99 mA, and the latter to log dc voltage transmitted from A/D converter. AC/DC logger was also installed to monitor ac voltage and cathodic protection potential, in which zinc was used as reference electrode. Using above systems, ac current density, AC voltage and cathodic potential were monitored over one week at each test site continually during test period. Soil resistivity was measured by Wenner 4 point method with 2 m of electrode spacing. Harmonics were also measured at test site using portable oscilloscope.

Each coupon was recovered after 0.5 and 1 year burial at each site. Excavated coupons were etched in Clark solution to remove corrosion products and weighed to 0.1 mg order. Corrosion rates were calculated from weight loss.

Resistance variation in MLETR probe with time was monitored manually or by its logger designed for continuous recording.

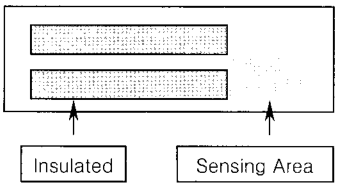
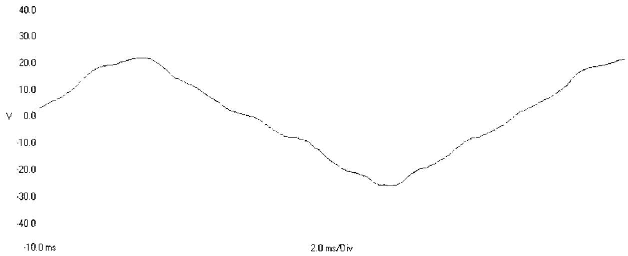


Fig. 1. Schematic diagram of MLTER probe.

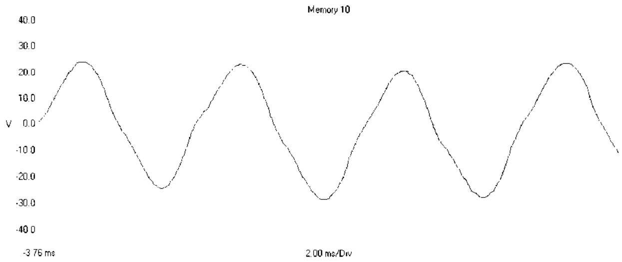
3. Results and discussion

As shown in Fig. 2, AC wave observed at test sites was one of single 60 Hz, 180 Hz and mixed harmonics. Single 60 Hz was measured at sites where resistive coupling by leak current in small grounds like traffic signal poll and inductive coupling existed. Single 180 Hz was attributed to harmonics from distribution line. Mixed harmonics was a result of combination of above two frequencies.

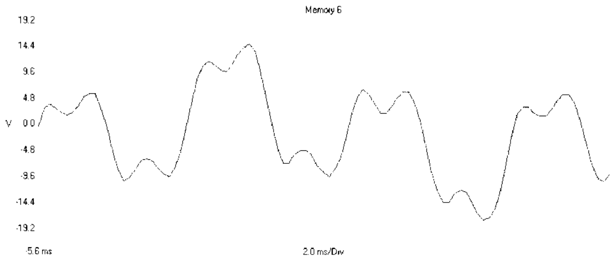
In Fig. 3, exemplary plot on AC voltage, corresponding ac current and cathodic protection potential monitored on site is shown. In which, AC voltage oscillated with time, AC current density also oscillated with correspondence to AC voltage while cathodic protection potential kept constant at -1.5V on-potential.



(a) 60Hz dominant frequency



(b) 180Hz dominant frequency



(c) mixed frequency

Fig. 2. On-site monitored AC voltage profiles.

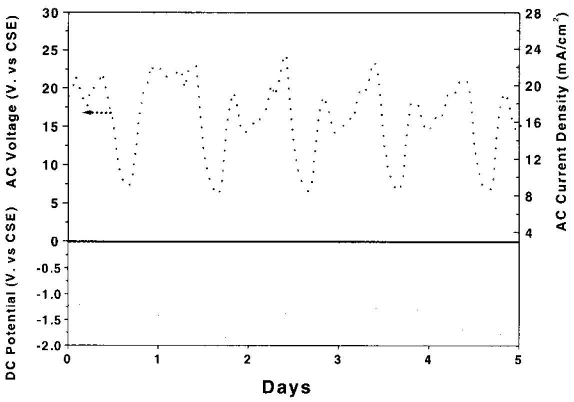
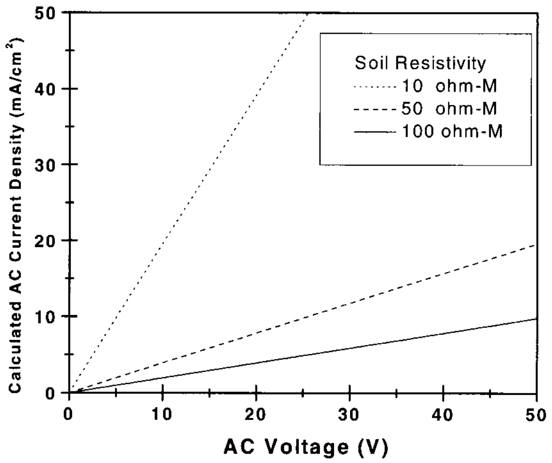
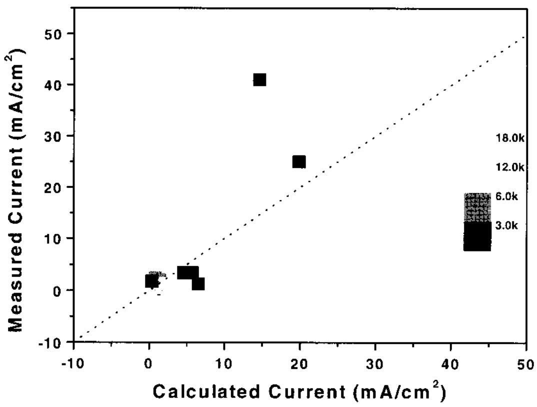


Fig. 3. An exemplary plot on the on-site monitored parameters such as AC voltage, corresponding AC current density and cathodic protection potential.



(a) Calculated AC current density plot on AC voltage under constant soil resistivity, coupon area condition.



(b) Plot for comparison of measured current density with calculated AC current density.

Fig. 4. Comparision of measured AC current density of coupon with calculated current considering AC voltage and soil resistivity.

AC current density was measured and compared with calculated ac current density by substituting values such as ac voltage, soil resistivity and given defect area into the equation {; $Iac = 8\ Vac/(\rho \pi d)$}.[14] Assuming that if ac voltage is constant, as shown in Fig. 4 (a), it is classic anticipation that more ac current will flow at low resistivity soil than at high resistivity soil. As shown in Fig. 4 (b), However, measured ac current is not consistent with calculated current. More or less current was measured in the range that current is small, but more current was measured especially when soil resistivity was below 3,000 Ωcm. This discrepancy can be explained by the factors that mean soil resistivity cannot represent soil resistivity at the soil contacting coupon where soluble water contents are different from site to site, and that AC current density in buried coupon can reach maximum when water containing various ions is wet on the surface of coupon.

In Table 1, results of monitored AC voltage, AC current density, cathodic potential and corrosion rate at each site are summarized. It is obvious that AC voltage cannot be related with corrosion rate rather than AC current density. Corrosion rates at CC1 and KN3 were 24 and 15 mpy respectively, though cathodic protection potential were met the criterion (; below -850 mV). In these sites, it was common that AC current density was high and frequency was 60 Hz. In contrast, corrosion rate at KI1 with comparable AC current density in KN3 was as low as 1/3 than that at KN3, which was resulted from frequency difference, i.e., frequency at KI3 site was 180 Hz. As shown in Fig. 5, corrosion rate results with 60 Hz has 3 times higher slope than that with 180 Hz, which is attributed to that reactance of capacitance decreases linearly with frequency. Regarding this phenomenon, Bertocci explained that, in randle circuit, most parts of ac current flow through the capacitor of electrical double layer

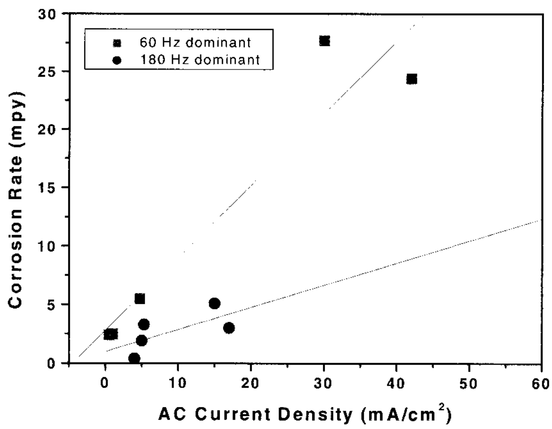


Fig. 5. Dependence of corrosion rate on AC frequency.

Table 1. Results of AC corrosion rate using coupon and monitored parameters.

Test Site	Corrosion Rate (mpy)			Monitored Parameters				
	Burial Time (mon.)			AC Voltage (V)	Cathodic On-Potential (V)	AC Current Density (mA/cm^2) (min.~max.)	Soil Reistivity (Ωcm)	Coefficient converted to 60Hz
	1	6	12					
KI1		2.98	5.69	8~24	-1.2 ~ -1.6	2~24	6180	0.40
KI2		3.27	2.31	3~8	-1.2 ~ -1.6	1~3	8101	0.43
KI3		0.45	1.93	3~8	-1.1 ~ -1.8	0.5~2	6280	0.41
KI4		3.19*	1.23	<1	-1.2 ~ -2.4	<1	1948	0.43
S2		5.51	2.78	10~20	-1.3 ~ -2.5	1~3	15072	0.79
S3		1.51	1.17	6~20	-1.0 ~ -3.3	1~8	2763	0.64
CC1		24.44		12~15	-0.9 ~ -1.6	20~40	2323	0.88
CC2		5.08	3.52	4~12	-1.2 ~ -1.7	<0.5	15028	0.59
CC3		1.67	1.43	<2	-1.1 ~ -1.8	0.5~2	4772	0.55
CC4		5.25*	2.14	<2	-1.1 ~ -1.6	0~4	3328	0.59
HN2	4.32	5.12		3~12	-1.1 ~ -1.8	2~10	9734	0.46
HN3		2.39	6.59*	<2	-1.0 ~ -1.5	<1	5228	0.82
HN4		2.47	3.76	<1	-1.3 ~ -1.7	<0.5	11930	0.74
KN1	6.37	1.47	2.65	14~22	-1.4 ~ -2.1	1~22	10048	0.50
KN2		1.93	1.95	3~8	-1.0 ~ -1.5	1~8	2951	0.33
KN3	15.3	17.78		3~5	-1.6 ~ -2.2	10~20	600	0.96
KN4		2.46		<1	-1.0 ~ -2.1	<0.5	1381	0.33
KP2	2.33	2.14	3.16	6~11	-1.1 ~ -1.8	1~8	16328	0.43
KP3	2.44	2.41	3.13	2~5	-1.5 ~ -1.7	0.2~4	8792	0.61
KP4		1.08	7.78*	<1	-1.7 ~ -2.4	<2	2575	0.55

* : Microbiologically induced corrosion is involved.

without charge transfer and a few parts of ac current takes part in charge transfer.

It is seemed right approach to consider the frequency effect on corrosion rate in terms of effective current density. That is, in this work, effective current density was obtained as following. All the components of harmonics were analyzed into each frequency, and each ratio was divided by multiple integers referred to 60 Hz, and then added totally and multiplied by measured current. It can be expressed as following.

Effective Current Density (I_E) = Measured Current Density (I_M) x Σ(Ratio of Each Frequency/Multiple Integer referred to 60 Hz)

In cases microbiologically induced corrosion is not concerned, corrosion rates of coupon at the site of low AC current density and of higher frequency are below around 5 mpy, and have different value with burial time even though test site is same. The factor like surface wetting according to different water content with time can be inferred to explain the difference in corrosion rate between recovery times of coupon.

It can be noted that corrosion rate of 1 ~ 3 mpy was measured even when AC current density was as low as 1 mA/cm^2. This was attributed to the weight loss caused by etching, which was confirmed that 1 ~ 2 mpy could be corroding away during etching. Consequently corrosion rates in Table 1 can be regarded maximum under given condition. It can be also said that weight loss method using coupon has limit to detect relatively low corrosion rate.

In Fig. 6, SEM photograph shows corrosion product formed by AC corrosion, which shows that adherent, dense and non-porous corrosion product is present. And EDS analysis on the products in Fig. 6 shown in Fig. 7 confirms that no other element in bulk composition except oxygen was detected. This implies that AC corrosion reaction proceeds mainly with cathodic oxygen reduction.

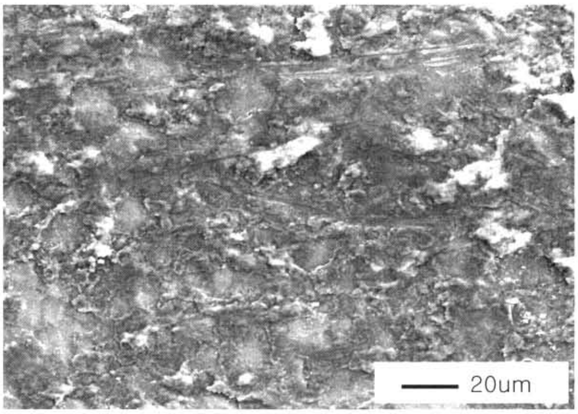


Fig. 6. SEM photograph showing corrosion products formed at AC interference field.

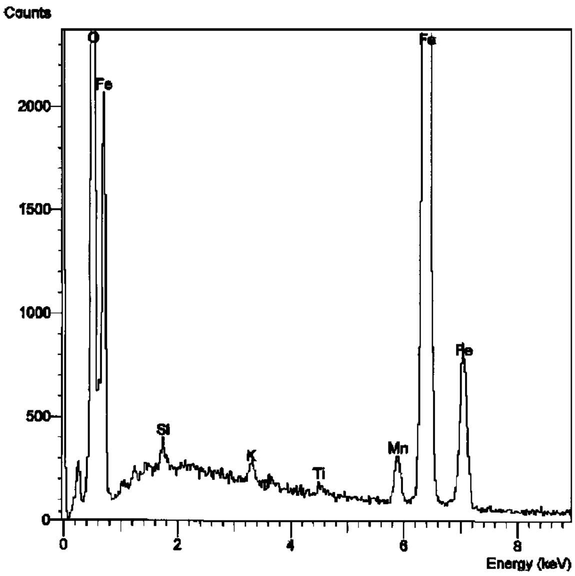
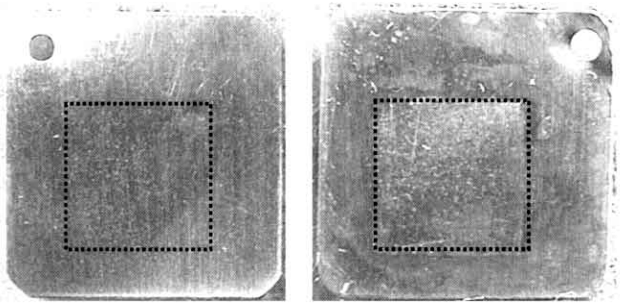


Fig. 7. EDS result on the corrosion products in Fig. 6.

Exposed coupon surface after removing corrosion product at etching solution is shown dotted rectangular line in Fig. 8. No noticeable corrosion is seen at KP4 6-month coupon with low AC current density in Fig. 8 (a), however, in Fig. 8 (b), because of higher AC current density, KI1 6-month coupon corroded even though cathodic potential had been maintained below -1.2V throughout test time.

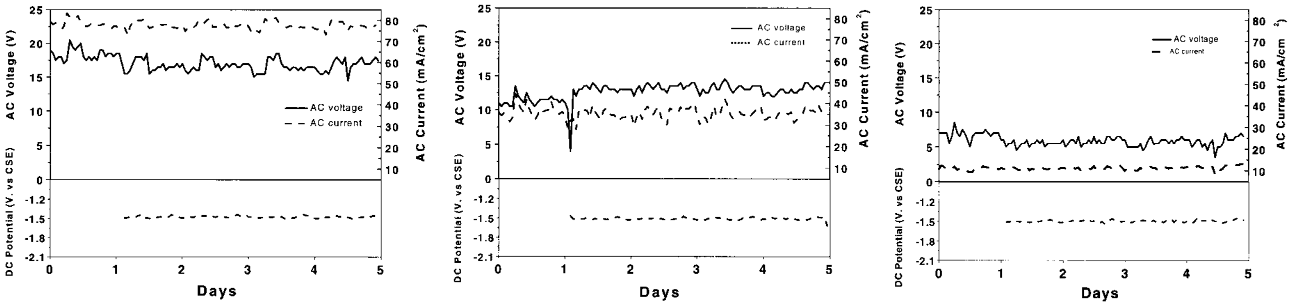
In real field, coating defect size is generally observed larger than 1 cm^2 like coupon size since most of coating defect is made by mechanical damage. Three simulated defect sized coupons (1, 4, 9 cm^2) were applied into three places with AC interference intensity for 6 months, where leakage current from signal poll grounds was present and formed AC voltage gradient with distance. With decreasing AC intensity, A, B and C sites are denoted. Single 60Hz was main frequency.

In Fig. 9, AC voltage and current density at 1 cm^2 coupon at each site are shown, in which cathodic potential was maintained at -1.5 V during test period regardless of site. However, AC voltage and AC current density were decreasing from the interfering AC grounds. AC voltage



(a) negligibly corroded (b) moderately corroded

Fig. 8. Photographs showing corroded surface after removal of corrosion products in Clark solution (⬚: exposed area to AC interference).



(a) A site (b) B site (c) C site

Fig. 9. Monitored results of AC voltage, AC current density and cathodic potential at CH1 place (A, B and C site is denoted from AC interference source).

and AC current density were 23 V, 80 mA/cm^2 respectively at A site, decreased to the degree that 7 V, 10 mA/cm^2 at C site.

Corrosion rates of coupon with different size at each test site are plotted in Fig. 10. Corrosion rate of 1 cm^2 coupon showed highest rate among coupons at same site. Though 1 cm^2 coupon was not recovered at A site because the edge of coupon connected to lead was corroded away, corrosion rate of 1 cm^2 coupon at B site was 24.7 mpy and corrosion rate decreased significantly with coupon area (: corrosion rates of 4 and 9 cm^2 coupon were 9.5 and 2 mpy respectively). This trend was same at C site. This could be explained in view of AC current that AC current didn't increase with proportion of coupon area, i.e., AC current in 9 cm^2 coupon was only two times compared to that of 1 cm^2 coupon, which led to less current density in 9 cm^2 coupon resulting in low corrosion rate.[15] This

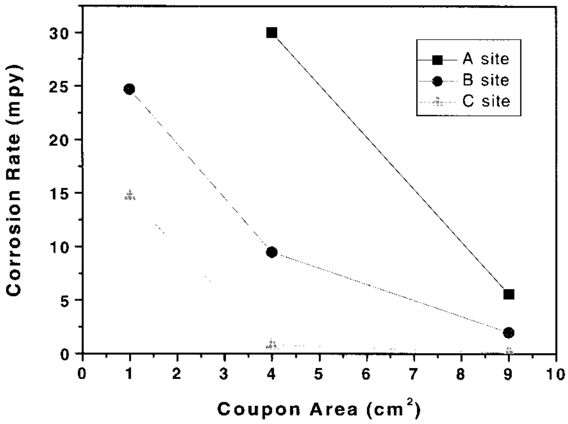


Fig. 10. Corrosion rates with different coupon area after 6-month test.

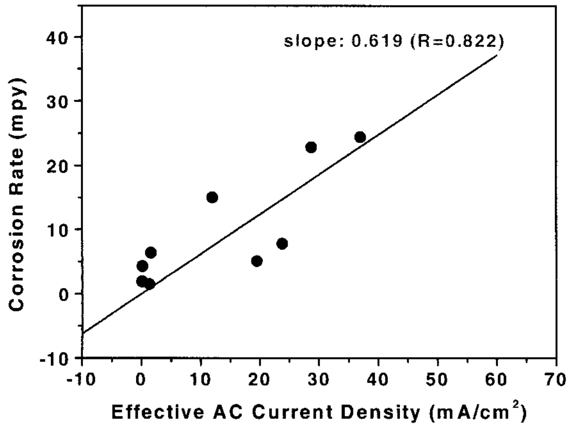
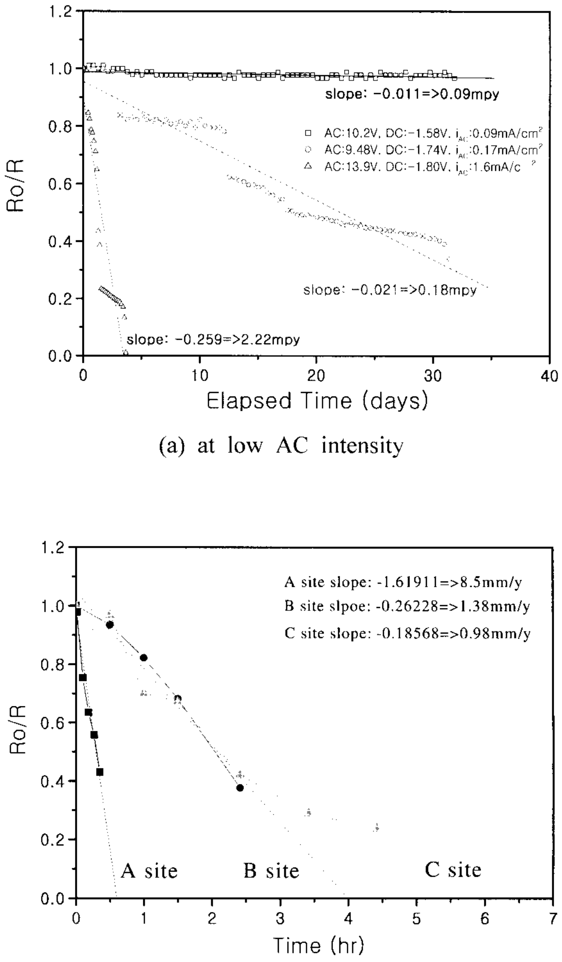


Fig. 11. AC induced corrosion rates with effective AC current density under cathodically protected condition.



(a) at low AC intensity

(b) at high AC intensity

Fig. 12. Behaviors of MLTER probe applied in AC interference field.

fact suggests that AC corrosion can be reduced in real field considering that coating defect size is normally larger than 1 cm^2 and AC corrosion do not proceed when defect size is as small as under 0.5 cm^2 like pinhole.

AC corrosion rate with effective AC current density is plotted in Fig. 11. AC corrosion rate increases linearly with effective AC current density under the condition of cathodic protection potential below -1.0V. Slope is 0.619 and correlation coefficient is 0.822.

Results of MLTER probe applied at same site of coupon in AC interference are shown in Fig. 12. Even at low AC interference intensity and cathodically protected condition (Fig. 12 (a)), discrete corrosion rates could be monitored in relatively short period compared to coupon method. At greater AC interference, corrosion behaviors could be also monitored effectively.

Corrosion rate results of MLTER probe are shown in Fig. 13. In Fig. 13, it was found that corrosion rate

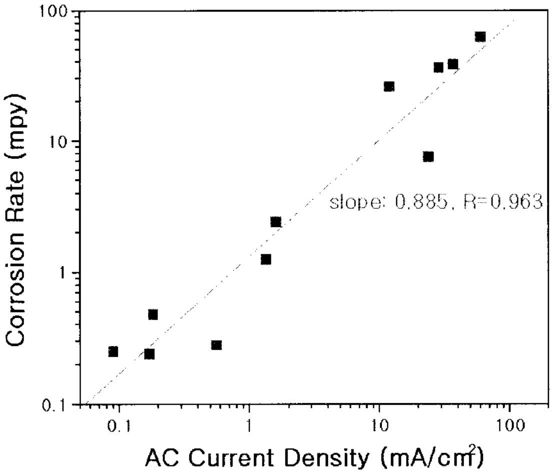


Fig. 13. Corrosion rates measured by MLTER probe with effective AC current density.

increased linearly with effective AC current density, its slope was 0.885 (R=0.963). The linear slope in results of corrosion rate measured by MLTER probe have steeper than that of coupon results, which is attributed by the fact that MLTER probe lines are dispersed and more AC current flow hereinto.

4. Conclusions

1) Measured AC current density at field showed significant deviation from those based on theoretically calculated equation [$I_{ac} = 8\ Vac/(\rho\pi d)$] especially when soil resistivity was below 3,000 Ωcm and measured AC current was over 5 mA/cm^2.

2) As field data, it was found that AC corrosion rates with 60Hz frequency was 3 times compared with those with 180Hz. Therefore it could be suggested that AC corrosion rate be evaluated in terms of effective current density: [Effective Current Density (I_E) = Measured Current Density (IM) x Σ(Ratio of Each Frequency/Multiple Integer referred to 60Hz)].

3) AC corrosion rate was increased linearly with effective AC current density under the condition that cathodic potential had been maintained below -1.0V, in which slope was 0.619 and correlation coefficient (R) 0.822.

4) AC corrosion rates obtained by MLTER probe showed comparable behaviors with coupon method, which suggests that MLTER probe be used as practical corrosion monitoring tool in buried pipeline where AC interference exists.

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