

Evaluation of Corrosion Effects on Permanent Ground Anchors

영구 지반앵커에 대한 부식의 영향 평가

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요 지

극성저항 계측법과 전기화학 임피던스 분광학을 이용하여 영구적 지반 앵커의 부식율을 계측하는 절차를 제시하였다. 극성저항 계측법을 이용하여 대표지반의 종류와 철의 부식률에 관한 특성관계를 도출하였고, 전기화학 임피던스 분광학을 이용하여 시간의존 부식 반응과 다양한 종류의 코우팅 시스템의 평가, 그리고 시멘트 그라우팅이 부식에 미치는 영향에 대하여 각각 평가하였다. 실험 결과 점성토와 사질토의 pH 지수가 5이하인 경우 부식발생이 용이한 지반으로서 영구적 지반 앵커의 부식반응에 심각한 영향을 미치리라 판단된다. 또한 중성 또는 알칼리성의 지반은 부식진행이 관찰되지 않았으며 부식률은 pH지수에 관계없이 일정한 결과를 보였다. 포셀린 점성토의 경우 pH지수의 변화가 철의 부식에 매우 낮은 영향을 미쳤다. 한편 시멘트 그라우팅의 사용은 철의 부식율을 약 0.003-0.01mm/y 정도로 낮출수 있었으며 에폭시 혼합 코우팅의 경우도 부식의 영향을 받지 않고 원 상태를 유지할 수 있어 매우 효과적으로 부식효과를 감소시킬 수 있었다.

Abstract

The corrosion rate measurement procedure for the permanent ground anchors using polarization resistance measurements and electrochemical impedance spectroscopy is presented in this paper. The polarization resistance measurements were used to determine the correlation between corrosion rate in the steel and soil characteristics. The electrochemical impedance spectroscopy was used to predict the time dependent corrosion reaction and evaluate the different type of coating systems and the effect of cement grouting on the corrosion attack under various conditions. The results indicate that a low pH soil is a good indicator of a corrosive soil. The low pH soil condition (<5) in both clay and sand has a significant effect on the corrosion reaction of steel members in permanent ground anchors. In the case of neutral and alkaline conditions beyond pH 6 in clay and sand, no consistent acceleration of corrosion was measured and the corrosion rate was constant regardless of variations of soil pH levels. Laboratory test data for porcelain clay indicate that the change of soil pH level has a small influence on the corrosion reaction in the steel member. The use of cement grouting in the bonded length is sufficient to decrease the corrosion rate to a level close to 0.003~0.01mm/y at the end of the given period. With epoxy and fusion bonded epoxy coating, the steel specimens remained unaffected and retained the original condition. It is suggested that epoxy and fusion bonded epoxy coating can provide effective protection against corrosion for a long time even in aggressive environment.

Keywords : Corrosion rate, Electrochemical impedance spectroscopy, Permanent ground anchors, Polarization resistance measurements

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1. Introduction

Ground anchors have been very useful for carrying the loads exerted on a structure and restraining the displacements of the structure in a variety of environments (Weatherby, 1982). Recently, permanent anchor systems have been popular for the design of retaining walls due to their long-term durability and performance.

To ensure long-term integrity and stability of ground anchors, especially permanent ground anchors, corrosion phenomena and protection systems become an important issue. Since most permanent anchors are designed to last longer than 25 years, it is necessary to monitor and study the long-term corrosion performance of ground anchors. Among the factors that affect the corrosion rate of steel embedded in soil are soil conductivity, soil pH, water content, soluble salts, redox potential, and aeration. Each of these factors may affect the anodic and cathodic polarization characteristics of a metal in a soil. For this study, however, only the soil pH was considered as the major factor affecting the corrosion rate of a metal.

As a portion of laboratory testing, potentiodynamic polarization measurement was performed on several samples to establish a direct correlation between the corrosion rate and soil characteristics and to predict the time-dependent corrosion reactions. This paper also presents a study about coating systems and the effect of cement grouting on the corrosion attack under various conditions.

2. Background

2.1 Polarization Resistance Measurements

The polarization resistance measurement test performs a potentiodynamic scan, which changes the potential and then measures the corresponding current (Uhlig and Winston, 1985). This experiment was performed on the steel specimens to determine the polarization resistance, which determines the influence of the chemical and physical factors that limit the corrosion rate. The polarization resistance measurement can measure absolute

corrosion rates in less than ten minutes. By the correlation between polarization resistance obtained from polarization plot and conventional weight loss, the corrosion rates under given condition can be obtained.

When a metal is exposed to a given corrosive environment, it develops a certain potential, corrosion potential (E_{corr}), where the anodic current density is numerically equal to cathodic current density, and corresponds to the corrosion current density (i_{corr}). Thus, the current measured with an external device will be zero. If a potential differing from E_{corr} is applied to such an electrode, a net current will be observed due to the difference of anodic and cathodic current. This result forms the polarization curve in terms of potential and current. A polarization resistance measurement is performed by scanning through a potential range (± 20) which is very close to E_{corr} . Polarization resistance (R_p) can be calculated from the polarization curve slope at a given potential range as expressed in Equation 1 (Corrosion and Electrochemistry Research Laboratory, 1987).

$$R_p = \Delta\phi / \Delta i = \frac{\beta_A \cdot \beta_C}{2.3(i_{corr})(\beta_A + \beta_C)} \quad (1)$$

where

$\Delta\phi / \Delta i$ = the slope of the polarization resistance plot,
 β_A, β_C = the anodic and cathodic Tafel constants determined from a Tafel plot, and
 i_{corr} = the corrosion current.

The corrosion current (i_{corr}) can be obtained from the polarization resistance expressed in Equation 2.

$$i_{corr} = \frac{\beta_A \beta_C}{2.3 R_p (\beta_A + \beta_C)} \quad (2)$$

Since the corrosion current is directly related to the absolute corrosion rate, it can be obtained from the Equation 3 (Fontana, 1986).

$$\text{Corrosion Rate (mm/y)} = \frac{w}{tA} = 0.00327 \frac{i \cdot E.W.}{D} \quad (3)$$

where

i = the corrosion current density in $\mu\text{m}/\text{cm}^2$,

A = the surface area,
 $E.W.$ = the equivalent weight in grams, and
 D = the density in g/cm^3 .

The Tafel extrapolation method is used to determine corrosion rate using data obtained from cathodic and anodic polarization measurements. In order to develop the polarization curves, the steel specimen is termed the working electrode, and cathodic current is supplied to it by means of a counter electrode. The potential of working electrode is measured with respect to a reference electrode by a potentiometer-electrometer circuit shown in Figure 1.

The voltmeter shows the corrosion potential of steel specimens with respect to a reference electrode. Figure 2 illustrates the applied current polarization curve of steel specimens in terms of the potential and logarithm of applied current. Under activation control, this curve is

nonlinear at low currents, however, at high currents, it becomes linear on a semilogarithm plot. This region of linearity is referred to as the Tafel region. The total anodic and cathodic polarization curves are superimposed as dotted line shown in Figure 2. In Figure 2, noble means the positive direction of electrode potential, and active means vice versa. In order to determine the corrosion rate from polarization measurement, the Tafel region is extrapolated to the corrosion potential (E_{corr}). At the corrosion potential, corrosion current density (i_{corr}), point that the rate of evolution is equal to the rate of dissolution, can be obtained.

2.2 Electrochemical Impedance Spectroscopy (EIS)

The response of corroding electrodes to small-amplitude alternating potential signals of widely varying frequency has been analyzed by electrochemical impedance measurement. Bard *et al.* (1980) has expressed the time-dependent signal, $I(t)$, on an electrode surface to a sinusoidal alternating potential signal, $V(t)$, as an angular frequency (ω) expressed in Equations 4 through 6 respectively.

$$Z(\omega) = V(t)/I(t) \quad (4)$$

$$V(t) = V_0 \sin \omega t \quad (5)$$

$$I(t) = I_0 \sin(\omega t + \theta) \quad (6)$$

where

θ = phase angle between $V(t)$ and $I(t)$.

Since the electrochemical processes absorb electrical energy at discrete frequencies, it causes a time delay and phase angle between excitation and response signals. Networks of electrical components such as resistors and capacitors can explain the electrochemical processes and reactions. In this report, the Bode plot, which consists of the Bode magnitude and phase plot, was used to analyze the data. The Bode magnitude plot can be obtained from the magnitude of the impedance versus the frequency in log scale. The Bode phase plot displays the relationship between the phase shift and the frequency in semi-logarithmic scale. A resistor has an impedance which is

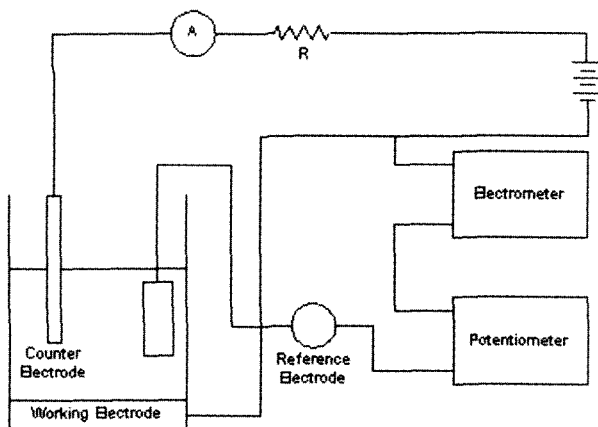


Fig. 1. Electric circuit for polarization measurements

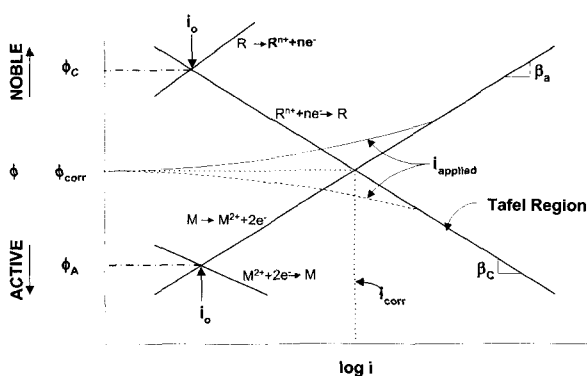


Fig. 2. Polarization curve of a corroding metal - Tafel Extrapolation, ϕ = Corrosion potential (Uhlig, 1985)

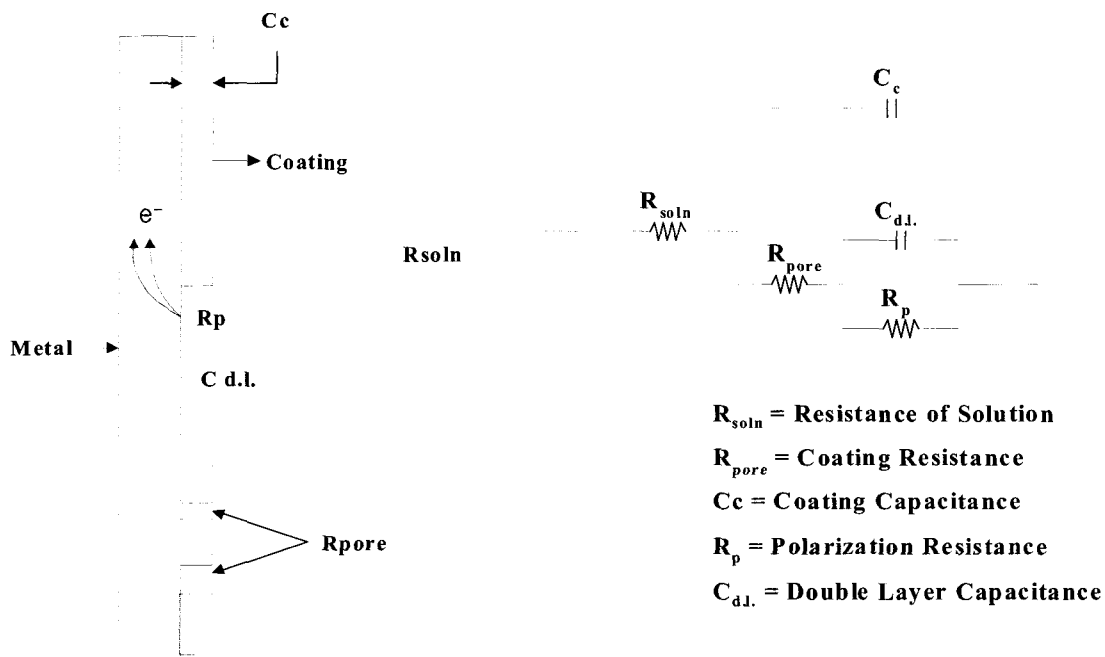


Fig. 3. Equivalent electronic circuit for a coating specimen (Corrosion and Electrochemistry Research Lab., 1987)

independent of frequency and has zero phase. However, a capacitor has an impedance, which decreases linearly with frequency and has a 90-degree phase angle.

Electrochemical reactions allow the use of equivalent electrical circuits for evaluation purposes. Resistors and capacitors represent the electrical properties of various components of the coated specimens and electrolyte. The use of electrical circuits is the basis of Electrochemical Impedance Spectroscopy (EIS). EIS is an AC system that measures the resultant impedance at a given frequency. Impedance measurements are taken over a broad frequency range ($10^{-3} \sim 10^4$ Hz). The results expressed in terms of impedance are used to find the representative values for the resistors and capacitors for these circuits.

Figure 3 shows the equivalent electronic circuit for a coating specimen. The solution resistance, R_{soln} is the resistance of the electrolyte between the reference electrode and the working electrode. The polarization resistance, R_p , is the charge transfer at the electrode/solution interface or more specifically at the anodic and cathodic reaction. The double layer capacitance, C_{dl} , is an electrochemical capacitor formed by the interactions of ions from the solution and the specimen at the surface of the substrate. Pore resistance, R_{pore} , is a reflection of

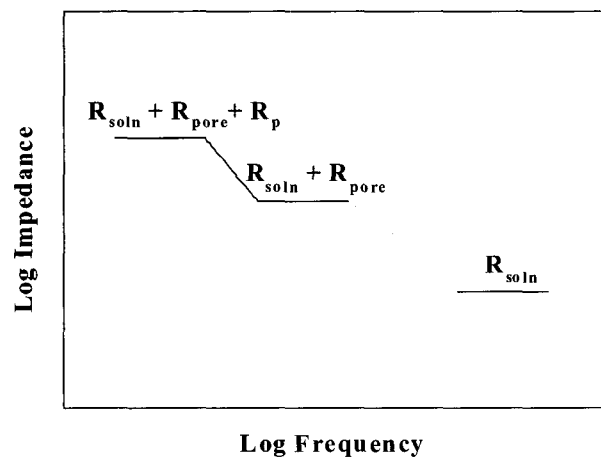


Fig. 4. Bode-Magnitude plot for a coating specimen (Corrosion and Electrochemistry Research Lab., 1987)

penetration of the coating by the electrolyte. In the case where no penetration of the coating by the electrolyte has occurred, the pore resistance is not observed in the Bode plot.

At low frequencies the capacitor acts as an open circuit and measurements of the various resistance in series can be performed. At high frequency the capacitor acts as a short and the solution resistance can be measured. Figure 4 shows the results for the Randles circuit which are typically presented in Bode-Magnitude plots.

3. Materials and Testing Procedures

3.1 Soil and Steel Specimens

Three types of soils, such as porcelain clay, clay, and fine sand, were prepared for potentiodynamic polarization measurements. Porcelain clay is well known and also called as Kaolinite. The liquid and plastic limits of clay were 53.7 and 20.9%, and the specific gravity of fine sand was 2.64 respectively. For the variation of soil pH, NaOH and HCl solutions were added to natural soil samples. According to the ASTM standard D-4972-89, the pH of the sets of soil samples was measured. Conductivity measurements indicated the relative ability of a medium to carry electrical currents. Soil electrical conductivity test was performed in accordance with a procedure developed by Bredenkemp and Lytton (1994). Table 1 summarizes the pH values and electrical conductivity of soil samples as measured in the laboratory. ASTM 1018 steel plates were chosen because of representative of a carbon steel and availability. The steel plates are 150mm×100mm in size and 5mm in thickness.

3.2 Test Procedures for Potentiodynamic Polarization Measurements

These experiments are designed to provide a comparison of the corrosiveness of steel in different soils. Polarization resistance measurement (PR) and Tafel

extrapolation (TE) require the application of a potential and corresponding current to the steel specimen being examined, with simultaneous measurement of the potential and current. In the case of PR the collected data is processed to calculate the polarization resistance and to estimate the corrosion rate of the steel specimens. As a result of polarization over a given potential range, TE is able to measure corrosion current by extending the line in Tafel region to the corrosion potential. The laboratory procedures to obtain measurements are as follows.

1. Place calomel reference electrode in the soil sample in the environment cell, insuring that the electrode is not in contact with the steel specimen.
2. Place the counter electrode (platinum wire) in the soil sample near the reference electrode.
3. Connect red wire of voltmeter to reference electrode.
4. Connect green and black wires to working electrode.
5. Measure the corrosion potential at equilibrium condition.
6. Scan the potential and measure the applied current at each potential.

The effects of soil environment on the ground anchor steel were determined by measuring the corrosion current (i_{corr}), corrosion rate, and corrosion potential for five different pH condition in the soil.

Table 1. pH and electrical conductivity of soils

Clay		Sand		Porcelain Clay	
pH	Conductivity (mS)	pH	Conductivity (mS)	pH	Conductivity (mS)
4.4	2.09	4.7	0.2	4.0	0.67
6.2	0.73	5.2	0.19	5.0	0.17
7.3	0.35	6.2	0.06	6.7	0.21
8.0	0.51	7.0	0.07	8.2	0.49
10.2	1.02	9.7	0.35	9.6	0.45

Table 2. Physical properties of soils tested

Soil Type	Soil Classification	Liquid Limit (%)	Plastic Limit (%)	Specific Gravity
Clay	CH	77	27	2.60
Sand	SP-SM	N/P	--	2.66
Porcelain Clay	CH	58	28	2.50

3.3 Test Procedures for Electrochemical Impedance Measurements

Electrochemical impedance measurements were also used to determine the effects of coating systems and cement grouting on the steel specimens. The experiments were carried out by measuring corrosion rates as a function of time in several samples and the results were compared with each other. The following list presents the sample conditions to be tested.

1. A natural soil with the acrylic coated and uncoated steel surface.
2. Cement grouting and soil with the acrylic coated and uncoated steel surface.
3. A natural soil with the painted epoxy coating.
4. A natural soil with the fusion bonded epoxy coating.

The following presents the test procedures for measuring corrosion by EIS.

1. The environment cell design was prepared as shown in Figure 5. The soil was compacted in a 66mm diameter environment cell. The diameter of soil and grout specimen is 65mm. The surface of the steel plate was sanded to remove the light rust and degreased in methanol before use.
2. The surface of the steel plate was coated using acrylic, epoxy, and fusion-bonded epoxy.

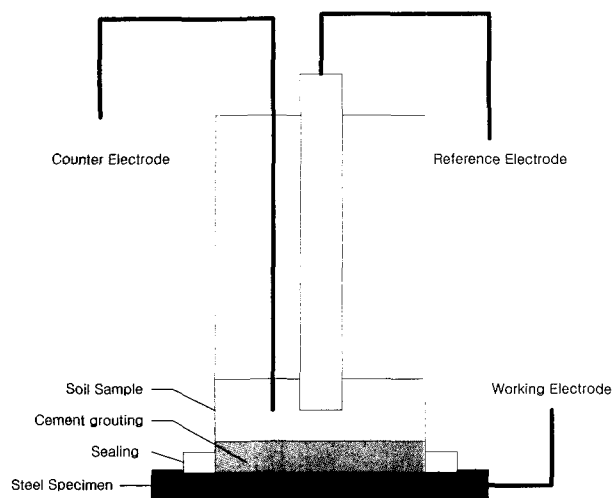


Fig. 5. A schematic of environment cell design for electrochemical impedance measurements

3. The grouting was made of Portland cement and water by mixing, with a water/cement ratio of 0.40. The grout was cured for a day in an air condition and, then for a week in water to prevent the propagation of cracks in the surface
4. The soil covering the grout surface was maintained as 20% moisture content to simulate the field condition.

4. Test Results and Discussions

4.1 Potentiodynamic Polarization Measurements

Polarization resistance measurements (PR) and Tafel extrapolation methods (TE) were used to determine corrosion rates for all the different soil-pHs. Figures 6 through 10 show the variations of corrosion potential, corrosion current, polarization resistance, and corrosion

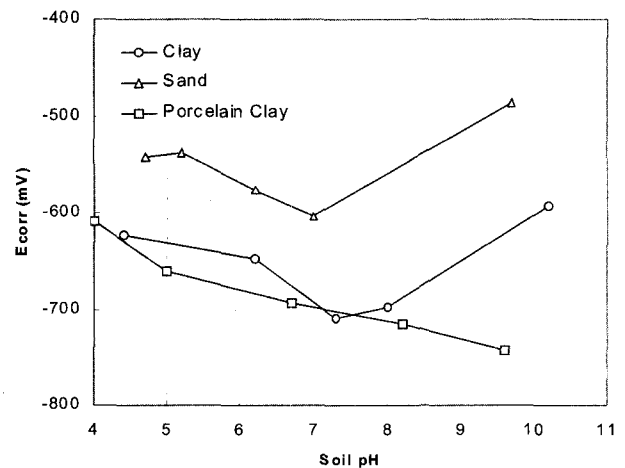


Fig. 6. Corrosion potential with variations of soil pH

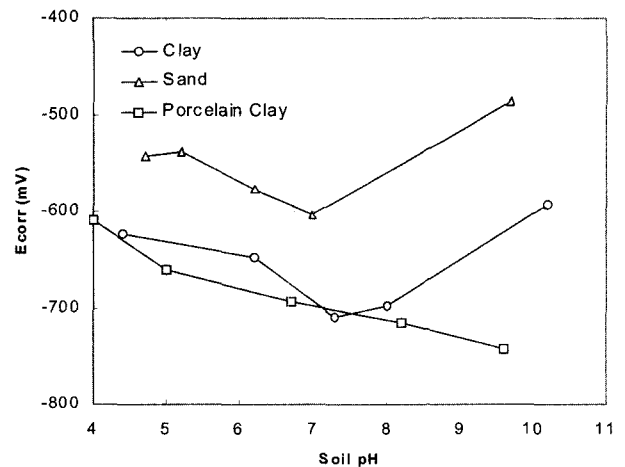


Fig. 7. Polarization Resistance with variations of soil pH

rate of the test specimens for different soil as a function of soil pH. Figures 9 and 10 show the corrosion rates for mild steel specimen samples embedded in different type of soils from PR and TE, respectively. For clay soils, the corrosion rates estimated for pH 4.4 samples were 0.214mm/y from PR and 0.261mm/y from TE, which indicated that a lower pH value causes a high corrosion rate. After pH 6.2 the corrosion rate sharply dropped to 0.031mm/y (PR) and 0.048mm/y (TE). The corrosion rates in the pH 7.3, 8, and 10.2 soil samples showed low values and maintained constantly with variations of soil pH. The natural pH of clay is 7.3 and suggests a low possibility of corrosion behavior in field condition.

The trend of sand samples is also similar to that of

clay samples. The data indicate the extremely acidic soil creates high corrosion rates of steel specimens. The measured corrosion rates at pH 4.7 were 0.250mm/y (PR) and 0.376mm/y (TE). The natural state of sand (pH 6.2) indicated the lowest corrosion rate (0.0054mm/y) when using Tafel extrapolation method. When using the Tafel extrapolation method shown in Figure 10, the corrosion rates in sand samples are generally greater than that in clay samples. This result indicates that the contact between the relatively pervious sand and the steel specimen was well oxygenated.

Measurements of corrosion rate in porcelain clay are carried out as a function of soil pH as a reference data. In general, the corrosion rate of steel specimen embedded in porcelain clay is independent of variations of soil pH.

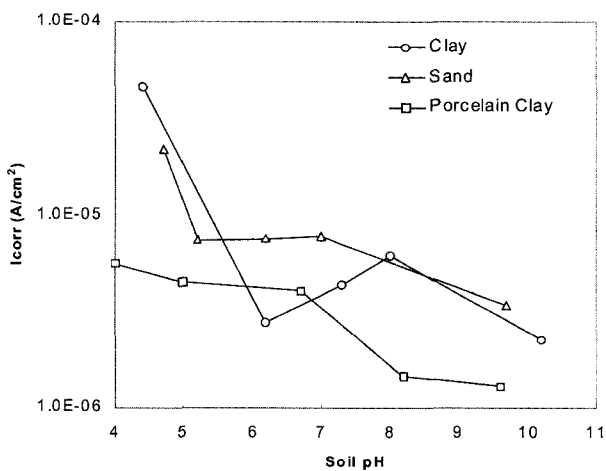


Fig. 8. Corrosion current density with variations of soil pH

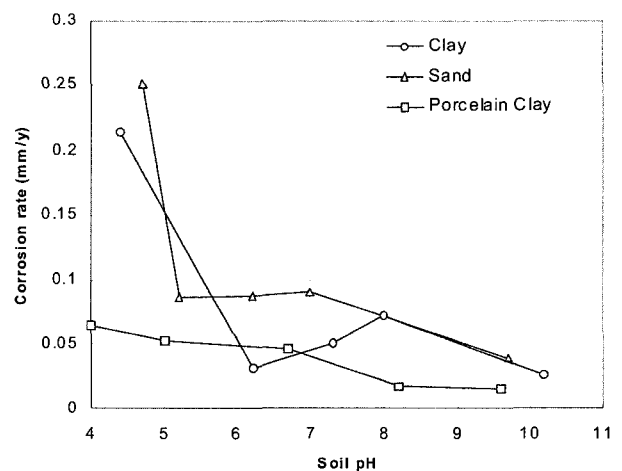


Fig. 9. Corrosion rate with variations of soil pH (Polarization resistance measurement)

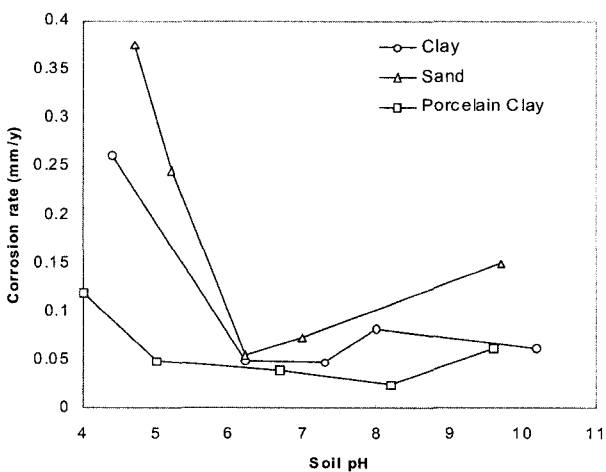


Fig. 10. Corrosion rate with variations of soil pH (Tafel Extrapolation Method)

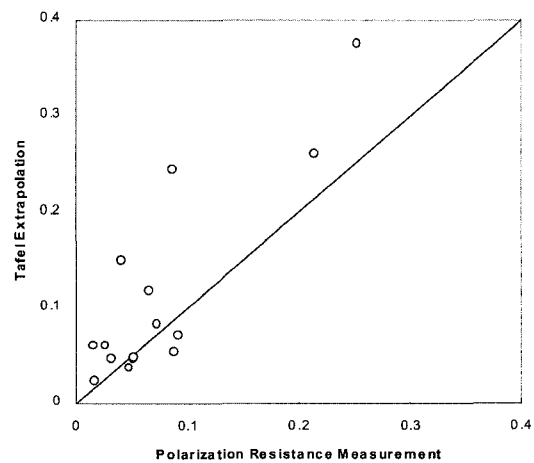


Fig. 11. Comparison of corrosion rates determined by two different methods

The steel specimen in high acidic porcelain clay (pH 4) shows a low corrosion rate (0.046mm/y (PR), 0.119mm/y (TE)). As a result of polarization resistance measurements, the range of corrosion rate with variation of soil pH is between 0.014 and 0.052 mm/y which is relatively uniform and significantly low. Figure 11 shows the comparison of corrosion rates determined by PR and TE. The corrosion rates determined by using TE are greater than those determined by using PR.

4.2 Electrochemical Impedance Spectroscopy

The purposes of these tests are the evaluation of the performance of coating/metal system and the effect of cement grouting against corrosion behavior. Electrochemical Impedance Spectroscopy (EIS) has been used successfully to determine the resistance of the electrochemical interface of interest to current under controlled condition. The laboratory tests were devised to simulate the possible cases of corrosion attack in permanent ground anchors. EIS results can aid in the selection of coating materials and guidelines of corrosion protection of permanent ground anchors.

Effect of Acrylic Coating on the Corrosion Rate

Figure 12 shows the Bode-Magnitude plots as a function of time for uncoated steel specimen embedded in only clay sample. The total resistance of steel specimen decreases with time. The decrease of polarization resis-

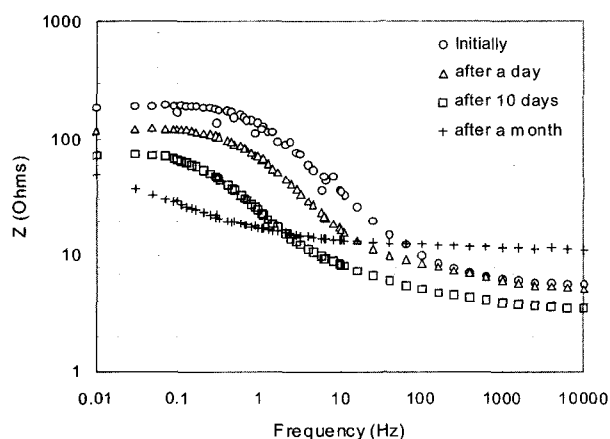


Fig. 12. Bode-magnitude plots as a function of time for an uncoated steel specimen in clay

tance indicates that the corrosion rates for steel specimens embedded in clay tend to increase as time passes. Based on the above Bode-Magnitude plots, the corrosion rates of steel specimens as a function of time under different environment can be determined. These results are shown in Figure 13. The corrosion rate for uncoated steel specimen after a month's exposure reaches about 0.34mm/y, which is significantly larger than any other cases. The initial corrosion rate of steel specimen in natural clay value is about 0.07mm/y, which is almost equal to the value obtained from polarization resistance measurement. Since the grouting performs the alkaline environment around steel surface, the absence of grouting in the samples makes a great effect on the corrosion rate of steel members.

The corrosion rate at acrylic-coated steel specimen is slightly lower than that of uncoated steel specimen. The estimated corrosion rate after a month's exposure reaches 0.16mm/y. Even though the corrosion rate of coated steel specimen is lower than that of uncoated steel specimen, it is hard to determine whether the coating system using acrylic is effective to resist corrosion in this environment. As a result, the usefulness of an acrylic coating may be doubtful in wet conditions.

Effect of Cement Grouting on Corrosion Rates

When an alkaline environment (pH 11-13) surrounds the steel, it is possible to prevent corrosion of steel. The grout should be able to provide this alkaline environment.

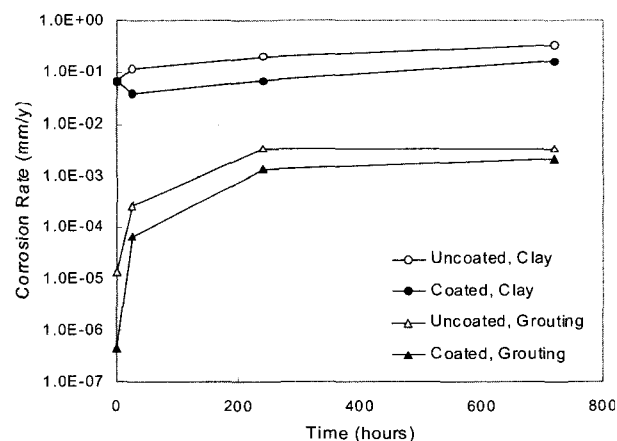


Fig. 13. Corrosion rate of steel specimens as a function of time

Hydrated cement has normal pH value of 12.6, which inhibits the presence of aggressive ions. At this pH condition, a passive film forms on the steel that reduces the corrosion rate to minimal levels. However, because of the damage of a passive film or the ingress of aggressive anions in the grout, significant corrosion phenomena may occur in steel tendons. The permeability of grout can allow carbonates and sulfates to react between the gases from the atmosphere and the cement grout. This reaction enables the pH of the grout to reduce and to increase the corrosion rate of steel at the same time. It is obvious that the thicker and denser the cement grouting, the more effective it is to inhibit corrosion in the steel member.

Uncoated steel specimens embedded with 5mm thick grouting were used for determining the effect of cement grouting on corrosion rates in the steel. Under these conditions, the steel is normally expected to be passivated due to the high pH environment. Initially, the grout cured for a week to allow the alkaline environment over the steel plate to form. The initial polarization resistance was estimated to be 10^6 ohms corresponding to 1.37×10^{-5} mm/y of corrosion rate. After a day's exposure, the total impedance drastically decreased to 5×10^4 ohms. This result indicated that the highly alkaline environment formed by grouting had deteriorated due to penetration of water and corrosive agents through the suspected fine crack over grouting. The corrosion rates after 10 days and a month's exposure were observed to be between 0.0034mm/y and 0.0035 mm/y, which indicated the corrosion rate was constant with time. Test results indicate that the use of grout had a great significance on the corrosion resistance of the steel. According to the study by Atimtay and Ferguson (1974), however, an increase in thickness of concrete cover greater than 50 mm does not significantly improve corrosion protection.

In addition, acrylic coated steel specimens embedded with 5mm thick grouting were used in the test. The initial corrosion rate was estimated to be the lowest value corresponding to 4.52×10^{-7} mm/y. Due to the degradation of coating system with time, the polarization resistance of coated steel specimen dropped in the range of 2×10^5

and 6×10^3 Ohms. Initially, the coated specimen showed much lower corrosion rate than uncoated specimen, however, as time passed, the difference in corrosion rates was reduced. So, the results indicated that the acrylic coating plays a lesser role in resisting soil corrosion.

Effect of coating system on corrosion rates

Figure 14 shows the comparison of corrosion rate for steel specimens coated by different types of materials. The tests were carried out in steel specimens covered by cement grouting which was the same condition as the previous tests. The samples coated with acrylic and epoxy showed initially low corrosion rates in the range of 5×10^{-8} and 2×10^{-7} mm/y. The coating systems initially create favorable barrier against corrosion, which results in high polarization resistance of the substrate. However, in the case of acrylic coating, the corrosion rates after 24 hours showed a trend of a large increase and then remained constant up to 720 hours reaching values of 0.001mm/y. This indicates that acrylic coating is not as efficient for underground corrosion problems.

5. Summary and Conclusions

The results of this study show that a low pH soil is a good indicator of a corrosive soil. The low pH (less than 5) soil condition in clay and sand has a significant effect on the corrosion reaction of steel members in permanent ground anchors. In the case of neutral and

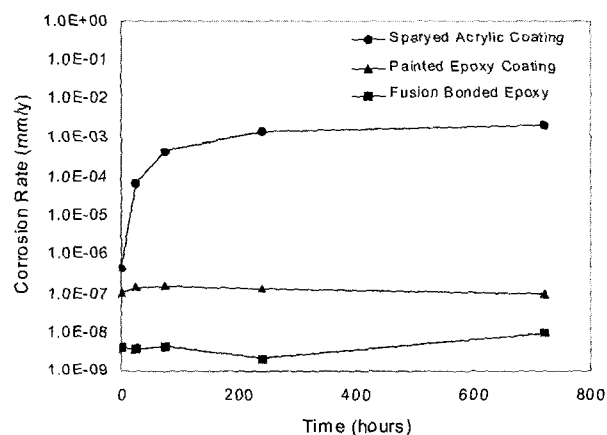


Fig. 14. Comparison of corrosion rates at different type of coating materials as function of times

alkaline conditions beyond pH 6 in clay and sand, no consistent acceleration of corrosion was measured and the corrosion rate was constant regardless of variations of soil pH levels. The soil samples with natural soil pH 6.2 (sand) to 7.3 (clay) indicated low possibility of corrosion attack to steel tendon. Under these conditions, measured laboratory corrosion rates were in the range of 0.05mm/y and 0.08mm/y. In contrast a different behavior was observed for porcelain clay. Tests results indicate that the change of soil pH level has a small influence on the corrosion reaction in the steel member and corrosion rates were below 0.05mm/y that is giving a longer effective performance.

In most cases, corrosion rates have remained very constant with time. Uncoated specimens covered by cement grout showed a low initial corrosion rate. However, as time passed, corrosion rate significantly increased and then after 10 days remained at a constant level. High corrosion rates and extensive rusting were observed in steel specimen embedded in clay without a grouting. The use of cement grouting in the bonded length is sufficient to decrease the corrosion rate to a level close to 0.003~0.01 mm/y at the end of the given period.

With epoxy and fusion bonded epoxy coating, the steel specimens remained unaffected and retained the original condition. With a coating thickness of 0.1mm, epoxy coating protected the steel specimen against corrosion irrespective of grouting thickness and the coating film

remained intact. It is suggested that epoxy and fusion bonded epoxy coating can provide effective protection against corrosion for a long time even in aggressive environment. Where the soil pH is above five, which is very aggressive conditions, the double protection against corrosion should be required in the permanent ground anchors. However, these protections are more expensive than single protection such as grout protection of the anchor length. If the soil resistivity is too low (<2,000 ohm-cm) and sulfides and chlorides are present, grouting protection hardly manages corrosion attack.

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