ORIGINAL ARTICLES

Relationship between Soil Properties and Corrosion of Carbon Steel

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ABSTRACT

Soils constitute the most complex environment known to metallic corrosion. Corrosion of metals in soil can vary from relatively rapid material loss to negligible effects, depending on soil environment. Soil engineering properties and soil contents are important parameters that influence soil corrosivity and level of corrosion dynamic. Previous researches had successfully prevailed in investigating the soil corrosiveness, but mainly focused on the soil chemical content instead of soil engineering properties. Hence, this paper investigates the relationship of soil engineering properties towards metal loss of X70 carbon steel coupons. The study focuses on three types of major soil engineering properties which are moisture content, clay content and plasticity index. A total of 84 pieces of X70 coupons were placed in seven different types of soils for 12-months to study the influence of soil engineering properties towards metal loss via weight loss method. The coupons were thoroughly cleaned prior to installation to avoid any contamination or any possible entities that can affect the corrosion process. The soil and coupon were placed into a poly-bag to let the coupon corrode naturally. Since the soil samples were collected from five different locations covering 500-km distance, the soils in the poly-bags were transferred from its actual site to a single location for monitoring purposes. Statistical analysis was carried out to study the relationship between soil engineering properties and corrosion rate. The analysis consists of simple bar graph, linear regression, multiple regression method and Analysis of Variances (ANOVA). The site testing results indicate moisture content as the most governance effect on corrosion rate based on the correlation coefficient. Yet, further investigation using the Analysis of Variances (ANOVA) and multiple regression analysis showed disagreement with the initial result whereby none of the factors have significance influence on corrosion rate. Hence, other factors such as soil chemical content, microbiological activity or pollution may be more dominant in influencing the dynamic of underground corrosion.

Key words: soil engineering properties, soil-corrosion, pipeline, carbon steel

Introduction

Soil-Corrosion Overview:

Corrosion is defined as a degradation of a material or its properties due to a reaction with the environment. Soil-corrosion is a complex phenomenon, with a multitude of factors/variables involved. Chaker and Palmer (1989) defined soil-corrosion as the deterioration of metal or other materials brought about by chemical, mechanical and biological action by soil environment. Buried steel pipelines are one of the most common mediums used to transport products such as crude oil and gas. These buried pipelines are exposed to various environment conditions such as seawater (offshore) and soil (onshore) that may experience corrosion attack. Steel pipelines deterioration due to corrosion attack is well known as a common and serious problem, involving considerable cost and may cause inconvenience to industry and to the public. The study of the soil as a corrosive environment is necessary due to the large number of buried pipelines and tanks, as their deterioration can appear to be a real economical and environmental problem through the years (Ferreira et al., 2007). There is always a chance that pipelines could leak or rupture leading to hazardous failure which can inflict human fatality and also badly damage the environment, assets and even humans due to explosion and leakage (Hopkins, 1995; National Energy Board, 1996; Yahaya et al., 2009). Although maintenances are done regularly, corrosion attack still remains as a serious risk to structure reliability and integrity.

Influence of Soil Engineering Properties on Corrosion:
Soil engineering properties and soil contents are important parameters that influence soil corrosivity and level of corrosion dynamic. Moisture content in soil will probably have the most profound effect when considering corrosion potential than any other factors. There are three types of sources which provide the soil moisture: free ground water, gravitational water and capillary water. Certainly, they have significant influence on the determination of corrosion growth. The free ground water is present in the soil below the surface and usually only river crossing pipelines are surrounded by ground water. In such condition, corrosion is regarded to occur in an aqueous environment. The main sources of gravitational water are snow, rainfall, irrigation and flood. This water enters and flows through the soil, governed by soil physical properties, including pore and capillary spaces at various zone in the soil profile. The capillary water represents an important reservoir of water in soil. Generally, corrosion rate increases with the increasing of moisture content.

Apart from moisture content, clay content may also contribute to the dynamic of underground corrosion. This has to do with its characteristic as the finest particle in soil. Soils are normally named and classified according to the size range of their particular size/grain diameter. For example, cobble (> 60mm), gravel (2mm-60mm), sand (2mm-0.063mm), silt (0.063m-0.002mm) and clay (<0.002m). Soil texture is one of the first factors to be considered during corrosion surveys because it determines the degree of aeration and the permeability of the soil (Velázquez et al., 2009). Soils with poor drainage due to its fine grain size, like clay and silt are more corrosive as compared to sand and gravel (good drainage). The study also looks into the contribution of Plasticity Index (PI) along with moisture and clay content. Plasticity Index (PI) is a measurement of the plasticity of soil, explained by the range of water content over which each type of soil has a plastic consistency. Soils with high PI tend to be clay, those with low PI tend to be silt, and those with PI of zero (0) tend to have little or no silt or clay.

Previous researches had successfully prevailed in investigating the soil corrosiveness, but mainly focused on the soil chemical content instead of soil engineering properties (Ferreira et al., 2007; Doyle et al., 2003; Liu et al., 2010). In most cases, study on the influence of soil engineering properties towards corrosion is hardly available due to an assumption that these parameters have minor or no effect on corrosion dynamic. Thus, this research is carried out to investigate the relationship between soil moisture content, plasticity index and clay content towards material degradation subject to underground corrosion.

Materials And Methods

Corrosion Study:

The main source of material used for this study is X70 carbon steel pipes from actual pipe segment. The pipes were machined into smaller size of coupons (40mmx60mm) using hot cut method. Cold cut method was then used to remove heat affected zone on the coupon which may cause changes in properties of the material (Noor et al., 2011). Coatings of those samples were removed (refer to Figure 1) to avoid inconsistent coating protection that might lead to bias result as well as to let the coupon to corrode under worst case scenario. The samples were thoroughly cleaned prior to installation to avoid any contamination or any possible entities that can affect the corrosion process. The procedures of the preparation and cleaning process referred to ASTM G01-03 (American Society for Testing and Material, 2003).

Fig. 1: Original coupon (with coating) and coupon after coating removed (right)
Simulated field works were carried out to measure the metal loss rate due to corrosion when steel coupons are exposed to various types of soils. There are seven types of soil collected from five different locations namely types 1 to 7. The soil and coupon were placed into a poly-bag to let the coupon corrode naturally (as shown in Figure 2). The procedures of preparing soil medium are referred to ASTM G162-99 (American Society for Testing and Material, 2010). Since the soil samples were collected from five different sites along East Coast Malaysia covering 500-km distance, the soils in the poly-bags were transferred from its actual site to a single location for monitoring purposes. The poly-bags were installed underground to simulate the soil-corrosion mechanism. A total of 84 steel coupons installed in 84 poly-bags whereby 12 steel coupons were allocated for each type of soil. Coupons retrieval was carried out periodically every three months. The retrieved coupons were not restored for later retrieval because the retrieved coupon is regarded as disturbed sample. The cleaning process will mess up the rust layer on the sample as a product of corrosion. In order to get a time-function data of metal loss, every single sample is assumed uniform in terms of strength, dimension and corrosion resistance. Hence, metal loss measurements from respective retrieval at different time within 12 months period are considered correlated with each other.

![Fig. 2: Site arrangement to simulate soil-corrosion mechanism](image)

The weight of the sample prior and after being exposed to soil environment was recorded to determine the metal loss and subsequently, the corrosion rate. Two cleaning methods were used to remove the impurities and corrosion product off the coupons, namely mechanical and chemical cleaning. The mechanical cleaning was carried out to remove the soil particles on the surface of samples using a soft steel brush. It was then followed by chemical cleaning whereby the samples were immersed in a pre-mixed solution (Hydrochloric acid + Hexamethylene Tetramine + Reagent water), as stated in ASTM G01-03(American Society for Testing and Material, 2003). Figures 3 and 4 show the physical look of the retrieved coupon before and after the cleaning process. Boisch (1970) mentioned that the difference in weight of the sample is most often used as a measure of corrosion or the basis for calculation of the corrosion rate. The average corrosion rate can be calculated using the following equation:

\[
CR = \frac{KxW}{AxDT}
\]

where;
- \(CR\) = corrosion rate (mm/y),
- \(K\) = a constant,
- \(T\) = time of exposure in hours to the nearest 0.01 hr,
- \(A\) = area in cm\(^2\) to the nearest 0.01 cm\(^2\),
- \(W\) = mass loss in g, to nearest 1 mg (corrected for any loss during cleaning),
- \(D\) = density in g/cm\(^3\)
Determination of Soil Engineering Properties:

Soil samples in the poly-bag were replaced periodically to maintain its freshness and its original contents. The soil properties were measured repeatedly during coupon retrieval (three months interval) so that the average value of soil engineering parameters can be properly recorded for correlation and sensitivity analysis purposes. Moisture content, clay content and plasticity index testing were carried out according to BS1377-2:1990 (British Standard Institution, 1998).

Multiple Regression Analysis:

Regression analysis was used to produce an equation to predict corrosion dynamic using multiple independent variables related to soil properties. A typical multiple regression analysis models have the form of:

\[
y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n
\]

where;

\[y\] = dependent variables
\[\alpha\] = constant
\[\beta\] = coefficient of independent variables
\[x\] = independent variables
\[n\] = numbers of independent variables

Multiple regression and Analysis of Variance (ANOVA) test was performed at 95% confidence level to examine the combined effect of moisture content, clay content and plasticity index on corrosion rate of studied coupons.
Results And Discussion

Effects of Moisture Content:

Using bar graph and linear regression method, the average moisture content (Average M.C) and average corrosion rate (Average C.R) shared similar line pattern that reflect the possibility of correlation between moisture content and corrosion rate (refer to Figure 5). The corrosion develop faster by higher moisture content as shown by result of soil type 3 and type 5 and vice versa. Figure 6 shows the correlation between moisture content and corrosion rate. The coefficient of correlation, \( R^2 \) yielded a moderate value of 0.503 with the incline trend whereby corrosion rate increase with the increase of moisture content. This is in line with the previous mentioned theory.

Fig. 5: Relationship between corrosion rate and moisture content according to soil types

Fig. 6: Influence of moisture content towards corrosion rate

Effects of Clay Content:

Figure 7 displays the relationship between clay content and corrosion rate according to soil type. The result does not exhibit a clear trend between average corrosion rate and average clay content. The corrosion rate
increase for soil type 1 to 3 but the clay content does not show consistent trend. Similar pattern was found for soil type 4 to 6 where the increment of clay content does not reflect by the pattern of corrosion rate. The conclusion is conformed by a very low coefficient of correlation, $R^2 (0.042)$ which indicates poor correlation between both parameters as can be seen in Figure 8.

![Clay Content Influence](image1)

**Fig. 7:** Relationship between corrosion rate and clay content according to soil types

![Average Corrosion Rate Vs Average Clay Content](image2)

**Fig. 8:** Influence of clay content towards corrosion rate

*Effects of Plasticity Index:*

Similar to moisture content and clay content, Figure 9 was constructed for initial investigation on the relationship between corrosion and plasticity index for all soil types. The result shared some common agreement with the above finding for clay content. There are no distinct proofs on the influence of plasticity index on corrosion rate for most of the soil types, if not all due to unclear pattern between average corrosion rate and average plasticity index. Figure 10 illustrate the influence of plasticity index towards corrosion rate. The coefficient of correlation, $R^2$ yielded a small value of 0.282 with an incline trend which express the development of corrosion rate as soil plasticity increases.
Regression Analysis:

Multiple linear regression analysis method was used to further investigate the influence of the studied parameters towards corrosion rate. Table 1 shows the summary of regression analysis with the average corrosion rate as dependent variable (response) while moisture content, clay content and plasticity index are regarded as independent variables (predictors). The coefficient of correlation, $R^2$ for the regression is 0.732 while the value of adjusted $R^2$ decreased to 0.464 shows that approximately 46% of the variation in the dependent variable can be explained by the independent variables. This decrement may be due to the dependency among independent variables (such as clay content and plasticity index), thus result in higher variance of independent variables. The findings in Table 2 indicate the value of significance $F$ is greater than 0.05, therefore the regression is found to be statistically not significant to express the relationship between the response and predictors. This is agreed with the above mentioned value of adjusted $R^2$. Table 3 shows the coefficient of regression model and significance ($p$-value) of all predictors towards response. The regression model equation is shown in equation (3):
\[ CR = 0.124 + 0.002(M.C) - 0.003(C.C) + 0.004(P.I) \]  

(3)

where:

- CR = corrosion rate (mm/y)
- M.C = moisture content (%)
- C.C = clay content (%)
- P.I = plasticity index

The \( p \)-values of all independent variables (moisture content, clay content and plasticity index) are greater than 0.05 (tested significant level) which explains that these factors have no significant effect on the test parameter (corrosion rate). Although moisture content was determined to have some influence on corrosion rate via initial observation, however when combined its influence with clay content and plasticity index, their overall effect towards corrosion growth is not significant.

**Table 1: Summary of multiple regression analysis**

<table>
<thead>
<tr>
<th>Regression Statistics</th>
<th></th>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Multiple R</td>
<td>0.856</td>
<td>0.732</td>
<td>0.464</td>
<td>0.029</td>
</tr>
<tr>
<td>R Square</td>
<td>0.732</td>
<td>0.464</td>
<td>0.029</td>
<td>7.000</td>
</tr>
<tr>
<td>Adjusted R Square</td>
<td>0.464</td>
<td>0.029</td>
<td>7.000</td>
<td></td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.029</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>7.000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Summary of ANOVA analysis**

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>( F )</th>
<th>( \text{Significance F} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>3.000</td>
<td>0.007</td>
<td>0.002</td>
<td>2.731</td>
<td>0.216</td>
</tr>
<tr>
<td>Residual</td>
<td>3.000</td>
<td>0.003</td>
<td>0.001</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.000</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3: Summary of parameters estimation**

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>( t ) Stat</th>
<th>( \text{P-value} )</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.124</td>
<td>4.569</td>
<td>0.020</td>
<td>0.038</td>
<td>0.210</td>
</tr>
<tr>
<td>X Variable 1 (Moisture Content)</td>
<td>0.002</td>
<td>1.638</td>
<td>0.200</td>
<td>-0.002</td>
<td>0.006</td>
</tr>
<tr>
<td>X Variable 2 (Clay Content)</td>
<td>-0.003</td>
<td>-1.200</td>
<td>0.316</td>
<td>-0.012</td>
<td>0.005</td>
</tr>
<tr>
<td>X Variable 3 (Plasticity Index)</td>
<td>0.004</td>
<td>1.670</td>
<td>0.194</td>
<td>-0.004</td>
<td>0.011</td>
</tr>
</tbody>
</table>

**Conclusion:**

Based on simple linear regression done individually between corrosion rate and soil engineering properties, soil moisture content was found to have moderate influence towards corrosion dynamic at most of the soils, while clay content and plasticity index are on the other side of spectrum due to less distinct pattern of relationship between line graphs. Nevertheless, the ANOVA test and multiple linear regression analysis yielded contrary result whereby all parameters were found to be not significant against corrosion rate. The measured metal loss from the buried coupon is mathematically caused by so many factors including soil chemical contents, microbiological factor (such as Sulphate-Reducing Bacteria, SRB) and other third party factors such as pollution. This is in line with the previous statement which mentioned soil engineering properties may pose minor influence on corrosion rate, hence not the most influential factors. This shows that the measured corrosion rates from the loss of weight of buried steel coupon may be dominantly caused by other factors apart from the tested parameters.

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**References**


