CORROSION STUDY ON X70-CARBON STEEL MATERIAL INFLUENCED BY SOIL ENGINEERING PROPERTIES

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This thesis is especially dedicated to:
Lim Chin Hock and Tam Kam Ming,
My beloved family,
My supervisor, P.M Dr. Nordin Yahaya and co-supervisor, Dr. Norhazilan Md Noor
RESA members and friends,
Thank you for your unconditional love, knowledge and support for all these years.
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ABSTRACT

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 may influence soil corrosivity and level of corrosion dynamic. Previous researches had investigated the soil corrosiveness, but mainly focused on the soil chemical content instead of soil engineering properties. Hence, this research aims to investigate the relationship of soil engineering properties towards corrosion dynamic (metal weight loss and corrosion growth pattern) of grade X70 carbon steel material and to classify the soil properties according to power law constants, *k* and *v*. The study focuses on four types of major soil engineering properties which are moisture content, clay content, plasticity index and particle size. Actual field work, simulated field work and laboratory test have been carried out to measure the metal weight loss influenced by soil properties. Five sites located in the east coast of Peninsular Malaysia (Terengganu, Pahang and Johor) were identified for actual field work and seven types of soil were collected and brought to the Universiti Teknologi Malaysia (UTM) site in Johor Bahru for simulated field work. Laboratory work was carried out by exposing the steel coupons to different intensities of soil properties under controlled environment. Graphical and statistical analyses were carried out to study the relationship between soil engineering properties and corrosion dynamic. The analyses consist of simple scatter plot, identification of outliers, normality test, simple linear regression analysis (SLR), correlation analysis, principal component analysis (PCA), paired t-test and multiple regression analysis. Moisture content recorded the highest R^2 of 0.369 from single regression analysis. The significant *p-value* of moisture content, 0.041 from multiple linear regression is the only *p-value* that satisfied the limit of significant *p-value* of 0.05, indicates its superior dominance upon metal weight loss. PCA has classified moisture content into Component-1 of metal loss constant, *k* while plasticity index and particle size are grouped into similar component of corrosion growth pattern constant, *v*. Similar findings were also observed through *t-test*. As a conclusion, the research has indicated moisture content as the most governing factor on metal loss constant, *k* while plasticity index, particle size and clay content have strong to modest influence on corrosion growth pattern constant, *v*. The findings have revealed the importance of soil engineering properties upon the mechanism of corrosion modelling especially when power law principal is adopted to predict the future metal weight loss.

ABSTRAK

Kakisan logam di dalam tanah boleh berubah-ubah dari kehilangan bahan yang pantas sehingga ke kesan yang boleh diabaikan. Sifat-sifat kejuruteraan dan kandungan tanah merupakan parameter penting yang mungkin mempengaruhi tahap pengaratan di dalam tanah. Kajian terdahulu telah mengkaji tahap pengaratan di dalam tanah, tetapi kebanyakannya hanya menumpukan perhatian kepada kandungan kimia tanah berbanding dengan sifat-sifat kejuruteraan tanah. Oleh itu, sasaran kajian ini adalah untuk mengkaji hubungan di antara sifat-sifat kejuruteraan tanah dan dinamik pengaratan (kehilangan berat logam dan corak pertumbuhan pengaratan) bagi bahan keluli gred X70 dan juga mengklasifikasikan sifat-sifat tanah mengikut pemalar hukum kuasa, *k* dan *v*. Kajian ini tertumpu kepada empat jenis sifat tanah yang utama, iaitu kandungan kelembapan, kandungan tanah liat, indeks keplastikan dan saiz zarah. Kerja lapangan, kerja simulasi dan ujian makmal telah dijalankan untuk mengukur kehilangan berat logam yang dipengaruhi oleh sifat-sifat tanah tersebut. Lima kawasan yang terletak di pantai timur Semenanjung Malaysia (Terengganu, Pahang dan Johor) telah dikenalpasti untuk menjalankan kerja lapangan dan sebanyak tujuh jenis tanah telah dikumpulkan dan dibawa ke Universiti Teknologi Malaysia (UTM) Johor Bahru untuk kerja simulasi. Ujian makmal telah dijalankan dengan mendedahkan kepingan logam kepada sifat-sifat tanah yang mempunyai keamatan yang berbeza di dalam persekitaran yang terkawal. Analisis secara grafik dan statistik telah dijalankan untuk mengkaji hubungan di antara sifat-sifat kejuruteraan tanah dan dinamik pengaratan. Analisis tersebut terdiri daripada plot selerak mudah, pengesanan "*outliers*", ujian kenormalan, analisis regresi linear mudah (SLR), analisis korelasi, analisis komponen utama (PCA), ujian t-berpasangan dan analisis regresi berganda (MRA). Kandungan kelembapan merekodkan nilai R^2 tertinggi iaitu 0.369 daripada analisis regresi linear mudah. *Nilai-p* signifikan kandungan kelembapan, 0.041 daripada analisis regresi berganda merupakan satu-satunya *nilai-p* yang memuaskan had untuk *nilai-p* signifikan iaitu 0.05, menunjukkan dominasi terhadap kehilangan berat logam. PCA telah mengklasifikasikan kandungan kelembapan ke dalam Komponen-1 bagi pemalar kehilangan logam, *k* manakala indeks keplastikan dan saiz zarah dikelaskan ke dalam komponen yang sama bagi pemalar corak pertumbuhan pengaratan, *v*. Penemuan yang sama telah didapati menerusi ujian t-berpasangan. Sebagai kesimpulan, kajian ini telah menunjukkan kandungan kelembapan merupakan faktor utama yang mempengaruhi pemalar kehilangan logam, *k* manakala indeks keplastikan, saiz zarah dan kandungan tanah liat memberi kesan antara besar ke sederhana terhadap pemalar corak pertumbuhan pengaratan. Hasil daripada kajian ini telah mendedahkan kepentingan sifat-sifat tanah ke atas mekanisme pemodelan proses pengaratan terutamanya apabila model hukum kuasa diguna pakai untuk meramal kehilangan berat logam pada masa hadapan.

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LIST OF ABBREVIATION AND SYMBOLS

*	asterisk mark (significant value)
d_{max}	maximum pit depth
W_{loss}	corrosion rate calculated from weight-loss measurement
°C	degree Celsius
µm	micrometre
A	area in cm^2
a	regression coefficient
AFAT	all-factors-at-a-time
b	power coefficient
bc	bicarbonate content
bd	bulk density
C	carbon
c	interception of linear model
CC	clay content
cc	chloride content
CC_F	Clay Content (actual field work)
CC_{SF}	Clay Content (simulated field work)
Cl^-	chloride content
CR	corrosion growth rate
CR_F	Corrosion Rate (actual field work)
CR_{SF}	Corrosion Rate (simulated field work)
ct	coating type
D	density in g/cm^3 (X70 = 8.29 g/cm^3; X42 = 7.85 g/cm^3)
e^-	electrons
E_h	reduction-oxidation potential

Fe	iron
Fe^{2+}	ferrous ions
Fe_2O_3	iron ore/rust
H_2O	water
K	a constant (8.76 x 10^4 mm/y)
k	metal loss constant
$k_0, k_1, k_2...$	regression coefficient for metal loss
K-S	Kolmogorov-Smirnov normality test
LL	liquid limit
m	slope/regression coefficient of linear model
MC	moisture content
MC_F	Moisture Content (actual field work)
MC_{SF}	Moisture Content (simulated field work)
MIC	Microbiologically-Influenced Corrosion
ML_F	Metal Loss (actual field work)
ML_{SF}	Metal Loss (simulated field work)
MRA	multiple regression analysis
$n_0, n_1, n_2...$	regression coefficient for corrosion growth pattern
NGDS	Natural Gas Distribution System
O_2	oxygen
OFAT	one-factors-at-a-time
OH^-	hydroxyl ions
P/S	pipe-to-soil potential
$P_{0.cal}$	predictive pit depth
P_c	evaluation value of the environment
PCA	principal component analysis
PGU	Peninsular Gas Utilisation
PI	plasticity index
PI_F	Plasticity Index (actual field work)
PI_{SF}	Plasticity Index (simulated field work)
PL	plastic limit
pp	pipe-to-soil potential

PS	particle size
PS_F	Particle Size (actual field work)
PS_{SF}	Particle Size (simulated field work)
p-value	significant value
R^2	coefficient of determination
re	resistivity
rp	redox potential
RSM	response surface method
sc	sulfate content
Sig.	significant value
SLR	simple linear regression analysis
SPSS	Statistical Package for Social Science
SRB	Sulphate-Reducing Bacteria
S-W	Shapiro-Wilk normality test
T	time of exposure (hr)
t	elapsed/exposure time
t_c	thickness of the corroded layer
T_F	Exposure Time (actual field work)
T_{SF}	Exposure Time (simulated field work)
UTM	Universiti Teknologi Malaysia
v	corrosion growth pattern constant
W	weight loss (g)
W_0	initial weight
wc	water content
x	independent variable
y	year
y	independent variable
ρ	resistivity

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CHAPTER 1

INTRODUCTION

1.0 Overview

Corrosion is a common form of structure degradation that reduces both static and cyclic strength of a pipeline. Pipeline systems, commonly made from carbon steel, are utilised to transport products such as crude oil and gas from one point to another. The lines are exposed to environment of robust surroundings throughout its service life such as seawater, soil (underground) and atmospheric condition. All these types of surroundings may potentially trigger a corrosion attack, such as atmospheric corrosion, aqueous corrosion and underground corrosion. Underground corrosion is the deterioration of metal or other materials brought about by chemical, mechanical and biological action in soil environment (Escalante, 1989). It can lead to serious pipelines failure with high likelihood of fatalities such as explosion.

Pipeline failures represent a significant loss in terms of profit loss, asset loss and reputation loss. Heavy financial loss associated with production loss, repair or pipe replacements will be borne by pipeline owners. Therefore, awareness among structure owners in maintaining high reliability of their structural system has risen dramatically. For that reason, the need for an accurate estimation of corrosion rate plays an important role in determining corrosion allowances for structural designs, planning for inspections, and scheduling for maintenance (Wang *et al*., 2003). Corrosion rate or sometime known as metal loss rate is regarded as the amount of corrosion loss per year.

1.1 Background of the Problem

The deterioration of steel pipelines due to underground corrosion attack is a common and serious problem, involving considerable cost and inconvenience to industry and to the public. The likelihood that pipelines could leak or rupture is always there and a pipeline failure can constitute serious hazards to the environment, assets and even humans due to explosion and leakage (Hopkins, 1995; National Energy Board, 1996; Yahaya *et al*., 2009). Due to the nature of pipeline system that span long distances, repeated failures at different locations can pose vital threat and grave interruption to the safe operation of the line (Wang *et al*., 2011).

Existing corrosion mitigation programs are quite effective in combating corrosion problems for the entire pipeline system that spans long distances. The challenge is that for various reasons, corrosion mitigation program can fail to provide adequate protection in specific, isolated areas. The reasons may include soil conditions, cathodic protection shielding and interference, or inadequate inhibitor concentration. Buried underground pipelines are laid across various types of soil environments with different degree of corrosivity. These various surroundings and conditions may contribute to failures in coating, inhibitors or cathodic protection. Even though maintenances are done regularly, pipelines still face corrosion attacks due to corrosive environments that surround the structure (Peabody, 2001; Sosa and Alvarez-Ramirez, 2009; Wang *et al*., 2011). In pipeline integrity and corrosion, the two most important questions to a pipeline operator are the severity of the corrosion and the deteriorating rate of the pipeline. Soil engineering properties and soil content are important parameters that may have some influences on the corrosion dynamic of buried pipelines. The term of corrosion dynamic refers to the process of degradation of metal over time. The problems are that these factors do not affect the pipeline equally at all locations and hence, corrosion defects do not grow at the same rate throughout the length of the pipeline. If the operators can identify those corrosion defects which are active and the factors that influence the corrosion rate; then predictions of future corrosion severity for each and every defect can be made.

1.2 Research Problem

Established empirical corrosion models incorporating soil parameters such as chloride content, pH, sulphate and soil resistivity are available to predict the progress of metal weight loss of steel structure in soil (Rossum, 1969; Li, 2003). Nevertheless, the incorporation of soil engineering properties such as plasticity index, clay content and particle size is lacking as compared to soil contents due to an assumption that these parameters do not govern the rate of metal loss underground. The assumption is not backed by strong empirical proof. If the governance of these parameters can be proven, its inclusion in the future corrosion model will become necessary.

Earlier research works on corrosion modelling for underground surroundings had leaned towards corrosion progress based on power law patterns (Ramanoff, 1957). In order to utilise power law model, parameters which contribute towards corrosion dynamic must be classified into two groups of constant namely metal loss constant (k) and corrosion growth pattern over time (v). Previous works classified the soil parameters into constant k and v using statistical inference based on multi regression method since the measurement of metal weight loss was done on site (Mughahghab and Sullivan, 1989; Velazquez *et al.,* 2009). Hence, the variation of metal weight loss due to the change of soil parameters intensity was not feasible. In fact, the metal weight loss of steel on site was actually caused by so many factors. Moreover, the exact numbers of factors that contribute to the metal weight loss during on site experiment is always unknown. This make the single correlation between selected soil parameter and metal weight loss from on-site results prone to errors since real environment is very random and unpredictable. Hence, may jeopardise the accurate classification of soil parameters into the right group between both constant k and v. Therefore, a parametric study based on one-factor-at-a-time (OFAT) approach under a controlled environment is crucially needed. OFAT approach allow modification on only a single factor at a time which can provide better understanding on the degree of influence of soil properties towards corrosion dynamic (Frey *et al.*, 2003).

1.3 Research Objectives

The main aim of this research is to investigate the relationship between soil engineering properties which are moisture content, plasticity index, particle size and clay content towards corrosion dynamic as experienced by buried gas pipeline using multi-regression and (OFAT) approaches. The objectives of this research are:

1. To determine the metal loss rate of carbon steel coupon installed in underground environment.

2. To classify the soil engineering properties into metal loss constant (*k*) and corrosion growth pattern over time (*v*) based on field work and parametric study.

The outcome may contribute to the knowledge of soil-corrosion behaviour by enriching the parameters selection for future corrosion modelling.

1.4 Research Scope

Although there are many factors may influencing the corrosion growth in steel, this research focuses on investigating the relationships between metal weight loss and soil engineering properties which are moisture content, clay content, plasticity index and particle size. Other parameters such as soil contents are not considered so that sole relationship between soil properties and corrosion rate can be identified. Field work and laboratory experiments are carried out to measure the metal weight loss of coupons buried in the soil, simulating the corrosion process that may occur for steel pipeline. The field work covers five different areas near existing onshore pipelines routes across three states in Peninsular Malaysia, which are Terengganu, Pahang and Johor. The steel coupons used to measure corrosion rates are prepared from actual segments of steel pipe of grade X70. Statistical analysis and multi regression techniques were utilised to identify the relationship between soil engineering properties and corrosion dynamic.

1.5 Importance of Study

The main challenge on developing predictive corrosion model is to have better understanding on the parameters selection to improve model accuracy. Previous research rarely takes into account soil engineering properties in the development of corrosion model and corrosion growth projection. The outcome of this research may answer the level of influence of soil engineering properties upon corrosion dynamic. If proven significant, future development of new corrosion model for buried steel pipeline can be improved by incorporating more parameters related to soil engineering properties.

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